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A Preliminary Study on the Quantitative Assessment of Building Information Modeling and Virtual Reality in Supporting Mechanical, Electrical, and Plumbing Plan Comprehension in AECO Education

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Abstract

Mechanical, Electrical, and Plumbing (MEP) systems are complex, often leading to conflicts and cost overruns. Yet, limited literature explores how to improve MEP plan reading in the classroom. The authors sought to fill the limited research gap through a pilot quantitative comparative study. Therefore, the effectiveness of Building Information Modeling-Virtual Reality (BIM-VR) implementation in a classroom to enhance MEP plan reading comprehension and spatial cognition was investigated, as many students struggle to interpret 2D plans due to their intricate nature. BIM-VR models were developed, and a group of students with limited prior-experience were chosen to minimize prior knowledge biases. Participants were randomly assigned to control and test groups and tested in two phases. The control group was provided 2D plans only, while the test group was granted access to BIM-VR models during the post-phase. Pre- and post-quizzes and a questionnaire were used to evaluate BIM-VR effectiveness, employing appropriate statistical methods. The test group performed similarly in the pre-phase and outperformed the control group in the post-phase. The questionnaire results indicated enhanced visualization, error detection, and a positive experience. The study findings promoted the need for academia to adopt BIM-VR, specifically within the context of MEP plan reading, to prepare students for industry demands.

Categories: Project Management, Building Information Modeling (BIM), Innovation and Technology Management
Keywords: mechanical electrical and plumbing (mep), building information modeling (bim), virtual reality (vr), computer-assisted learning, plan reading

Introduction

Building Information Modeling (BIM) and Virtual Reality (VR) have gained traction in the architecture, engineering, construction, and operations (AECO) industry [1,2]. It was reported that the application of BIM in the AECO industry significantly grew from 28% in 2007 to 71% in 2012, and in 2023, Autodesk reported that BIM utilization had reached 80% [3-5]. The growth is attributed to BIM's advantages, including enhanced visualization, efficient and accurate scheduling, cost estimations, and facilitation of collaboration and communication of all involved parties [6-8]. On the other hand, VR allows for an immersive spatial experience and offers added benefits when integrated with BIM applications, such as developing safety training scenarios with no real perceived risks, simulating site visits for inspection purposes, and facilitating effective communication between client and builder [1,9,10].

Mechanical, Electrical, and Plumbing (MEP) systems are intricate and critical components of any construction project due to their high cost and complexity [11]. These systems compromise about 40%-60% of the project cost and labor [12]. By 2013, 60% of the construction industry reported utilizing BIM to enhance MEP coordination [13]. However, the combined application of BIM and VR and their potential have not been fully explored in teaching MEP-related courses [3,14]. As previously mentioned, integrating BIM-VR in a construction project provides several advantages. Therefore, those advantages naturally extend into a project’s MEP components. Some of the benefits specific to MEP systems include detecting spatial conflicts in the early phases of a construction project, which enables the avoidance of rework and has the added benefit of cost and time reductions. Furthermore, there is recorded evidence that using BIM combined with VR reduced the risk of injuries related to MEP work and improved productivity [12].

When considering the benefits both BIM and VR offer when integrated, they can allow for an enhanced learning experience in the classroom of AECO programs by improving visualization and spatial cognition. However, most AECO education programs still depend on traditional methods of 2D project drawings and infrequent site visits, with limited utilization of 3D technologies [15]. This lag in adopting 3D-related technologies into the classroom subsequently led to a lack of BIM-trained professionals who are in high demand as the industry increases its dependency on BIM-VR applications [3,16]. Therefore, introducing a BIM-VR integrated methodology into AECO programs’ MEP curriculum can offer significant advantages to

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the students, as BIM-VR can enhance their understanding and perception of said systems. Also, this benefits the industry by providing students with training in BIM-VR for their future careers.

This study aims to add to the limited body of knowledge on BIM-VR applications in teaching MEP plan reading. Specifically, the study seeks to evaluate the effectiveness of BIM-VR as an MEP plan reading teaching method by quantitively comparing learning outcomes between a control group and a test group (details on the two groups can be found in "Combined control versus test" section). Additionally, student feedback on the perceived effectiveness of the BIM-VR approach will be collected through surveys to provide preliminary insights into its impact on learning outcomes. The study also aims to provide a replicable approach to BIM-VR adoption to aid in wider adoption in academic settings. Through the evaluation, BIM-VR benefits are emphasized, encouraging its adoption in academia, better preparing students and young professionals for industry demands. The study objectives are further detailed in "Step 5: data analysis" section.

The following subsections of the literature review will start with a discussion of BIM-VR application in industry, move to BIM-VR in education, then BIM-VR in MEP systems, and end with BIM-VR adoption challenges. The aim is to provide a comprehensive literature on the BIM-VR adoption status across industry and education as a whole, focusing on MEP systems. The literature review was utilized to optimize the study.

A quick definition for certain technologies referenced in the paper, along with a summary of BIM-VR, BIM-AR, MR, and Metaverse in MEP education applications, is provided below in the following bullet points and detailed in Table *1* [17,18]:

• Building Information Modeling (BIM) is a multidimensional process that integrates technologies, policies, and roles to create virtual, information-based models for managing project data throughout the lifecycle of a facility.

• Virtual Reality (VR) uses software to create immersive, realistic simulations involving images, sounds, and other sensations, allowing users to experience and interact with a virtual environment.

• Augmented Reality (AR) overlays computer-generated content onto the real world, allowing users to interact with both in real-time.

• Mixed Reality (MR) blends elements of both VR and AR, allowing digital content to interact with the real world while offering a flexible and immersive experience.

• Extended Reality (XR) is an umbrella term that encompasses VR, AR, and MR, referring to all real-and-virtual combined environments and human-machine interactions created through computer technology and wearables.

• Metaverse: the metaverse is a digital space that blends the real and virtual worlds. The users can interact with each other and the surrounding environment using XR hardware and advanced internet technologies.

This study utilizes a combination of BIM and VR to explore their potential for enhancing MEP plan reading comprehension.

Emphasizing BIM-VR in MEP education allows students to immerse themselves in complicated 3D models of a building. This provides a distraction-free virtual setting, which is ideal for understanding complex MEP systems by relating 2D plans to an immersive live 3D view. The approach enables virtual interaction with MEP layouts anytime, anywhere. It thus can potentially enhance spatial cognition and interpretation skills essential for practical applications. Given this characteristic, BIM-VR is particularly valuable in the preconstruction phase, where students can build foundational skills for analyzing MEP designs with drawings only and without access to the building.

In contrast, BIM-AR, MR, and XR can bring unique advantages by overlaying digital information in real-world environments. Thus, the approach will be more powerful during the construction phase, allowing real-time interaction with physical site contexts. This feature not only enables the accurate alignment of digital models of the MEP system with actual site conditions but also facilitates quick adjustments as needed. Although it is important, it is not the focus of this paper, as the intent is to teach students how to interpret MEP plans from scratch with the aid of real-time interaction with an existing site.

Technology	Phase of Application	Educational Focus	Advantages	Limitations in MEP Education
BIM-VR (Virtual Environment)	Preconstruction phase	Foundational MEP plan analysis	Provides immersive 3D models for complex MEP systems. Enables distraction-free setting that enhances spatial cognition and interpretation of 2D plans. Facilitates in-depth comprehension of MEP layouts anytime, anywhere. Enhances visualization skills critical for preconstruction understanding of MEP systems.	Lacks real-world environment cues. Limited for phases requiring interaction with actual site conditions.
BIM-AR (Augmented Content Onto the Real World)	Construction phase	On-site MEP system alignment and adjustment	Allows overlay of digital models onto real-world environments, enabling precise alignment with physical MEP components. Supports real-time adjustment and error correction with physical site context. Enhances situational awareness for practical on-site applications.	Less effective for initial MEP concept comprehension without a real-world context. Requires physical access to the site, limiting its use in early-stage training.
BIM-MR (Interaction Between the Real and Virtual World)	Construction and operation phases	Interactive on-site system analysis	Combines real and virtual elements, enhancing real-time data overlay on physical MEP systems. Allows virtual interaction with real-world structures, aiding inspection and maintenance tasks.	Complexity and higher setup cost. Focused on field operations rather than preconstruction learning objectives.
Metaverse (Fully Immersive and Interactive Environment)	All phases (preconstruction, construction, operation)	Comprehensive MEP system understanding	Provides immersive environments where students can engage in simulations of MEP systems across all project phases. Facilitates collaborative learning and real-time interaction with global teams in virtual spaces. Offers a safe space for hands-on practice without physical risk, enabling repeated training on complex MEP systems.	Requires access to high-end VR/AR hardware, which may be cost-prohibitive. Limited by the quality of the virtual models and simulations, which may not fully replicate real-world complexities.

TABLE 1: Comparison of BIM-VR, BIM-AR, BIM-MR, and Metaverse for MEP education applications

Note: XR is an umbrella term; thus, it was not added to the table. Instead, its components (VR, AR, and MR) were discussed. MEP, Mechanical, Electrical, and Plumbing; BIM-VR, Building Information Modeling-Virtual Reality; BIM-AR, Building Information Modeling-Augmented Reality; BIM-MR, Building Information Modeling-Mixed Reality

BIM-VR in the AECO industry

Many researchers have evaluated the application of BIM-VR in the AECO industry in various contexts. However, the combined BIM-VR research is limited compared to studies conducted on BIM applications within the AECO industry [8,19-22].

One study examined the effect of VR applications combined with BIM-3D models on improving cost estimation and stakeholder communication [23]. The study integrated a BIM model with pre-defined interchangeable materials with varying costs. Then, the model was linked to a VR game engine. The user can change the material as desired while the model details the effect on the project's total cost estimate within the VR environment. The study aimed to involve the stakeholders in the design process while highlighting the impact of material choice on cost. The authors also highlight that when the owner can make the desired esthetic and financial decisions early in the design process, change orders can be reduced; thus, construction costs are reduced [23]. The effectiveness of the developed approach was not tested or evaluated by participants.

Several studies evaluated the benefits of BIM-VR application within the context of safety [24,25]. In the first study by Zhao and Lucas, the VR-based safety program focused on reducing injuries/fatalities related to electrical hazards. The study aimed to utilize VR training as it offers a safe and interactive learning environment that has proven more effective than passive learning techniques [24]. The study presents a limitation where the developed training was not tested or evaluated for effectiveness. The other VR-based safety study focused on safety training in proximity to heavy machinery under several construction site scenarios [25]. A detailed construction site model was created to include dynamic interactions, action consequences, other needed characters, and site layout. The users were then asked to complete a simple task while their reaction time to a construction vehicle was recorded [25]. The study provides a potential application for more extensive safety training within the AECO industry, minimizing injuries/fatalities. The study was tested by a single user and presented the same limitation as the previous paper, in which the system was not sufficiently evaluated.

A VR system was developed for specific use at the construction site office to allow easy access to the BIM model [26]. The aim is to enable efficient interaction with the BIM model to navigate and inspect the components of the project. Therefore, it allows information extraction, measurement extraction, and model augmentation. The system was tested on four projects at different construction stages [26]. The site-personnel of each project evaluated the system through a questionnaire at the end of the virtual walkthrough; a total of 28 responses were collected. The study reported positive responses toward the system's ability to achieve pre-defined goals [26]. The study relies on questionnaire responses and recorded attitudes to evaluate the effectiveness of the proposed technology adoption approach.

A cloud-based BIM metadata server labeled BIM-VR real-time synchronization (BVRS) was developed in a study to streamline BIM-VR applications within the AECO industry [27]. The system was then implemented in an existing building. The VR model allows for alternative material choices and spatial-geometry manipulation, which are then updated within the BIM model. The study aimed to provide a more efficient, automated, and simplified use of BIM-VR in the AECO industry to promote its potential benefits [27]. The proposed technique was evaluated by testing whether the VR environment augmentation translated into the BIM model and proved successful. However, outsiders did not evaluate the proposed approach's effectiveness in testing for ease of use or the developed system's practicality from an industry or academia point of view.

A more specific approach was investigated to evaluate the BIM-VR application within maintenance and construction [1,28,29]. The investigation focused on the benefits VR combined with BIM can offer beyond enhanced visualization. The benefits extended into improved communication among all involved parties, maintenance schedule visualization, constructability, and alternative materials. The study also provides insight into several technologies and software packages/plugins that can be employed for the proposed BIM-VR applications. The research offers a detailed map for utilizing the BIM-VR combination to its full potential with all the required parameters to capitalize on its advantages [1,28,29]. Similar to previous studies, participants did not evaluate the proposed approach for effectiveness and practicality.

The highlighted studies on BIM-VR application within the AECO industry show positive attitudes toward the technology. Also, some research on the BIM-VR adoption trend shows a gradual increase in the adoption or motivation of applications [30,31]. Most studies used surveys and interviews to evaluate the attitudes with minimal quantitative analysis. Also, many of the studies listed focused on developing a BIM-VR adoption map but did not test the validity of the proposed approach.

BIM-VR in the AECO education

While there is extensive research on BIM-VR applications within the AECO industry, research on applications within the education sector is relatively less. Furthermore, even more limited studies analyze the effectiveness of BIM-VR quantitatively, with the primary focus being on attitudes through surveys or interviews (qualitative), as highlighted by this study's literature review.

Starting with the BIM applications within the AECO education environment, architecture programs were the first to adopt the technology into their curriculum, followed by engineering and construction programs [32]. In 2008, a survey revealed that less than 1% of universities had a stand-alone BIM course, with 9% introducing BIM into the curriculum through other courses [33]. In 2014, 54% of schools reported having stand-alone courses, with 52% introducing the content within other courses [34]. More recently, BIM adoption in education is still at a critical stage, and researchers strongly emphasize the need for academia to keep up with industry demands [35]. Another study evaluating the status of BIM adoption in higher education revealed that there is still a need for more research on BIM within academia to bridge the gap with industry needs [36].

VR adoption is on the rise but is yet to be fully explored, with studies emphasizing that among most XR research studies, ones focused on education compromise an extremely small portion [37-39]. Another study points out that VR adoption, among other XR technologies, still faces significant setbacks within the education environment [40], while other studies emphasize the need for more research [41,42]. The lag in the AECO education sector leads to gaps in the expected level of knowledge and training of students in the AECO industry [16,36]. In another recent study, evaluating the effectiveness of VR-based construction education for engineering students through different training scenarios states that there remains a lack of sufficient research on the matter [43].

A study on BIM-VR adoption in education provides a detailed framework for implementing BIM-VR within the classroom with recommendations on student assessment methods, lab setup, and VR equipment [3]. The study focused on adopting BIM-VR throughout the curriculum of the Construction Management program at Eastern Kentucky University. The study started with an extensive literature review that was used to optimize the proposed adoption framework. Then, the program curriculum was reviewed to identify courses where BIM-VR can be implemented and how course objectives can be achieved using the technology. Then, assessment and evaluation methods were developed to ensure the proposed approach was successful and aided in reaching course objectives. BIM-VR was adopted into eight courses ranging from the first to senior year of study. The suggested evaluation approach to assess the method's success is comparing student evaluation pre- and post-BIM-VR adoption [3]. However, in this study, the evaluation of the proposed technique was not discussed and was deferred to a future study. Another limitation is that the proposed method is not generalizable to all construction management programs. Still, the framework is detailed and clear so that it can be adopted to replicate similar adoption approaches to cater to the specific needs of other programs.

In a different BIM-VR study within AECO education, 2D drawings were compared with BIM-VR application in the classroom [44]. The study participants were graduate-level students split into two groups: one from the School of Building Construction at the Georgia Institute of Technology (Group A) and the other from the Civil Engineering program at the Pontifical Catholic University of Peru (Group B). A 3D model was developed along with the 2D drawings of the same model. The students were randomly assigned to start with either the 3D-VR model or 2D plans; if a student started with the 2D plans, they followed it with the 3D-VR model and vice versa [44]. After each round, the students would be asked to select the correct view from different isometric drawings of the structure. The groups' demographics varied in age, experience, program of study, and gender. There was a total of 19 participants, of which 15 were male, and the majority (79%) were under the age of 30. After, students were asked to complete a survey on their attitude toward the BIM-VR process. The scores were then reported for each group. Group A scored perfectly in both tasks of BIM-VR and 2D plans, while B scored higher in the BIM-VR portion. Also, the study reported that VR-aided visualization improved the performance of students rated with low spatial abilities prior to the study start, compared to 2D plans. The survey reported positive attitudes where the task was completed with less time. The study only analyzed the scores of the participants and survey, but no statistical analysis was discussed on the effectiveness of the proposed BIM-VR application.

Wang et al. evaluated the effectiveness of incorporating BIM-VR into the classroom of construction management students [45]. The students were divided into groups of full BIM applications, including VR and partial BIM applications. A Likert-scale questionnaire was distributed at the end of the study to evaluate the differences among the groups of BIM-VR and only BIM; a total of 65 responses were collected. As perceived by participants, the top-ranked benefit of BIM was the 3D modeling ability, followed by efficient quantity take-off and collaboration [45]. The group with BIM-VR found the experience to be more positive for their learning abilities about various construction components such as scheduling, cost estimation, clash detection, and visualization [45]. The study only incorporated the statistically analyzed results of the questionnaire with no quantitative analysis of the method's effectiveness on students' performance.

BIM-VR's role in improving design visualization for students to contribute to a better understanding of project material, concerns, and decision-making processes was evaluated in a classroom [46]. The study developed a model to highlight BIM-VR best practice adoption approaches in industry and education. A total of 23 students took part in the evaluation process of BIM-VR adoption in the classroom. The evaluation was collected as a survey of students' opinions and attitudes toward the effectiveness of BIM-VR adoption. Students reported positive feedback with increased motivation, learnability, and creativity when BIM-VR was incorporated.

Of the few studies that included quantitative analysis, students' spatial perception was tested [47,48]. Both studies used inferential statistics to compare groups' results with and without the BIM-VR experience. The results in both studies indicated that the students with the immersive environment outperformed the non-immersive experience. One study compared BIM versus BIM-VR [47], and the other 2D versus BIM-VR [48]. Also, one of the studies included a survey at the end of the study to measure attitudes [48]. The questionnaire indicated the students' positive attitudes toward the BIM-VR learning experience. Alternatively, the BIM versus BIM-VR study looked into factors influencing perception, including age, education level, profession, color blindness, familiarity with 3D resources, and previous knowledge of the selected building [47]. The demographics in that study, with a total of 30 participants, are 71% between the ages of 23-31, 57% male, 40%, 37%, and 23% graduate, undergraduate, and high school level, respectively. Also, the study included 44% architects and engineers, 23% architecture students, and 33% other professions [47]. There was a significant relationship between age, education level, and profession. As age and education levels increased, performance also improved, while engineers and architects outperformed other professions [47]. Demographics in other studies were not disclosed, with 33 participants from an entry-level construction and engineering management course. While both studies used quantitative analysis, the same group was subjected to different 2D or BIM versus BIM-VR evaluation modes. The overlap of evaluations can influence the data as there can be a learning curve between the tests.

BIM-XR in MEP systems

MEP systems cover various components, including heating, ventilation, and air conditioning, which fall under HVAC. MEP also compromises piping systems that include drainage, water supply, fire protection systems, as well as electrical fixtures and power [11]. With such complicated systems that typically exist within limited physical space in a building, their design and construction are complex. As previously highlighted, MEP systems are extensively involved in the schedule and cost of a project, requiring highly trained professionals.

Yet, the application of BIM-VR within MEP systems, whether in industry or education, is minimally explored with limited literature. A study evaluating research focusing on BIM application found that MEP papers compromised about 5.26% of the literature [49]. In a more recent investigation evaluating studies on BIM adoption in higher education for various AECO disciplines, MEP makes up an almost insignificant portion of those studies [36]. A similar sentiment is also observed in a study focused on BIM adoption for MEP systems in education, where it was reported that there is a lack of studies on BIM adoption for MEP systems within the classroom [50].

BIM-VR in MEP Systems (Industry)

The limited research creates a gap in knowledge of the effectiveness of BIM-VR applications, whether in industry or education. Therefore, this limits the potential benefits these technologies can offer the AECO industry and education. A previously highlighted study, authored by Ozcan-Deniz, explored several types of buildings with varying scopes of BIM-VR application [51]. One of the projects reported using BIM-VR to explore efficient pipe routing and clash detection. However, the study reported that BIM-VR application within MEP systems was minimal.

Immersive environment utilization within MEP systems varies depending on the purpose of the application, where AR and VR are the leading technologies. VR is typically used in the early construction phases to provide a virtual environment for the proposed project. VR enhances visualization and comprehension of the proposed MEP systems by enabling first-person interaction through the virtual environment. Therefore, VR allows for improved communication and collaboration, reduces costs and time, and facilitates clash detection early in the design phase [23,52,53]. Meanwhile, AR is applied in settings where information about the existing systems is needed. AR allows for efficient installation and assembly through access to digital information about the object of interest [11,54]. Also, AR reduces time and cost by optimizing inspection and maintenance tasks [54,55]. Other benefits include progress tracking, improved on-site productivity and collaboration, and defect detection [56,57].

BIM-VR in MEP Systems (Education)

Some studies investigated the application of BIM combined with 3D gaming engines for MEP system evaluation [15,58]. The first study explored BIM and a virtual 3D game engine for building operations. A BIM model was created with the architecture and MEP components of the building, which was then developed into a game simulation [58]. The model was augmented so the participant could interact with elements and receive information about material and function. The paper serves as a proof of concept for the applicability of creating an interactive learning environment for building components such as MEP through BIM and 3D game engine virtual walkthroughs. However, student performance or attitudes were not discussed.

The other research study utilizing BIM combined with a 3D game engine went further into analysis and evaluated the approach's effectiveness by testing it within an educational environment [15]. The study focused on HVAC systems and modeled the entire duct system of the selected building. The students participating in the study were evaluated through a quiz to test their comprehension of the presented HVAC systems [15]. One group was provided access to the 3D game engine, while the other was tested through conventional teaching methods. The group with access to the 3D game engine outperformed the other group in understanding the function and behavior of the MEP components. The study utilized a 3D game engine viewed through a screen, the same as a BIM model, but the immersive environment factor was not explored. Furthermore, applications such as clash detection and quantity take-off were not examined. The study mainly focused on the functionality and performance of MEP systems. A total of 45 students participated in the evaluation: 24 in the BIM group and 21 in the traditional teaching through the 2D visualization group. Participants' demographics were not discussed.

The BIM-VR application's effectiveness in accurately and efficiently detecting clashes versus traditional 2D methods was investigated [59]. The evaluation included studying the ability to detect clashes, the time required, and the number of clashes detected from the actual number. The study was evaluated by junior-level students who were familiar with the presented topic [59]. Students performed better on time and accuracy when BIM-VR was involved and were satisfied with the proposed teaching approach. However, the study neglected the learning curve effect from using the same participants in the 2D versus BIM-VR assessment, and the results were presented as overall scores with no statistical testing of pre-to-post evaluation along with survey responses. The participants were 15 third-year students, 12 male, three female, and a mean age of 22.

Another study with a similar approach used BIM-VR as an educational tool to create an interactive learning environment [60]. The participants were split into the control and test groups. The control group was tested on conventional 2D, and the test group was tested using BIM-VR through surveys and scores.

Students were tested on the structural and MEP components of a project. The BIM-VR group reported enhanced visualization and increased motivation but was outperformed by the 2D-based group in terms of time and accuracy [60]. The discrepancy in the results of this study was attributed to a lack of familiarity with the introduced BIM-VR system. The study only showed scores and time without statistical analysis and survey responses. The participants were 30 fourth-year civil, mechanical, and electrical engineering students. Each group had 15 students, comprising 11 males and four females, as well as 10 civil, three electrical, and two mechanical students.

Two more studies utilized a similar approach of incorporating BIM-VR into the education environment [61,62]. The first study followed a typical approach of creating a model incorporating MEP components where the user can retrieve information about the components within the VR environment [61]. The study provides a detailed integration map by providing specifics on the hardware and software to develop the BIM-VR framework. The students were asked to complete a survey on their attitude toward the introduced BIM-VR application within the education environment. The results showed a positive attitude toward BIM-VR, with increased motivation to learn as the highlight [61]. A total of 57 students responded that their years of study varied from first to third year and belonged to the 19-21 age group. There was no significant difference between male (44) and female (13) students in the evaluation, except for one question related to hidden MEP features comprehension [61]. The year of the study did not affect evaluation results, indicating BIM-VR can be incorporated early into the academic journey for first-year students to aid them in better understanding complex construction topics [61]. The questionnaire was the only form of evaluation based on self-reported attitudes, which can introduce some bias and uncertainty on the effectiveness of the proposed approach.

The following study focused more on MEP applications, with the difference of utilizing control and test groups in a pre-to-post evaluation approach [62]. The control group was tested only through a 2D plan, while the test was given access to BIM-VR. The study quantitatively evaluated the architecture students' ability to design sanitary systems such as hot/cold water pipes in a bathroom [62]. Both groups performed similarly in the pre-phase, indicating that both started at the same baseline of knowledge. However, the test group outperformed the control in the post-phase when they had BIM-VR access compared to only 2D plans access for the control group [62]. Also, the BIM-VR group reported the process as a positive learning experience with improved collaboration and interest in the proposed topic. However, the study did not assess the students' ability to perform tasks such as quantity take-off, identifying elements and their dimensions, or clash detection. A total of 43 students in their third year of the architecture program in a plumbing engineering course participated in the study. There were 22 students in the control group and 21 in the test group, and students' demographics were not disclosed.

The literature review serves as a tool to help the authors of this study develop an optimal experimental design to study the effectiveness of BIM-VR in MEP plan reading. Hence, it provides insight into project choice, assessment methods, and data analysis techniques which is further detailed under "Control group" section. A summary of the findings of the literature review is listed in Table *2*.

<table>
<tr><th colspan="2">Parameter</th><th>Focus</th><th>Key Findings</th><th>Analysis</th></tr>
<tr><td colspan="2">Section 1 .1.</td><td>BIM-VR in the AECO industry</td><td>BIM-VR utilization in the industry is steadily increasing. Utilization spans areas of cost-estimation, visualization, collaboration, communication, training, and safety.</td><td rowspan="4">Limited quantitative statistical research, with most studies focusing on attitudes and opinions, was obtained through questionnaires and surveys. Few studies adopt quantitative randomized design studies to obtain objective outcomes on BIM-VR influence. Some conflicting reports on the BIM-VR effect on improving comprehension compared to conventional techniques using 2D plans only.</td></tr>
<tr><td colspan="2">Section 1 .2.</td><td>BIM-VR in AECO education</td><td>Limited research on BIM-VR in education with more focus on outcomes with more emphasis on adoption. Mainly reports positive attitudes. Similar utilization areas to the industry were evaluated. Strong need for more training in academia to prepare individuals for industry demands</td></tr>
<tr><td rowspan="2">Section 1.3.</td><td>1.3.1</td><td>BIM-VR in MEP systems (Industry)</td><td>BIM-VR MEP systems research is limited VR is commonly used for the early stages of construction, improving visualization, collaboration, and communication, reducing errors, and, in turn, cost and schedule overruns. AR is commonly used when information about existing systems is needed, improving installation efficiency and reducing time and cost.</td></tr>
<tr><td>1.3.2</td><td>BIM-VR in MEP systems (Education)</td><td>BIM-VR research for MEP systems in education is limited. Most studies utilized BIM-3D or BIM-VR to enhance visualization and perform tasks like clash detection, design, and functionality identification. BIM-VR application in MEP systems education shows positive influence and attitudes.</td></tr>
</table>

TABLE 2: Literature review summary and findings

MEP, Mechanical, Electrical, and Plumbing; BIM-VR, Building Information Modeling-Virtual Reality; AECO, architecture, engineering, construction, and operation

BIM-VR adoption challenges

While BIM adoption in the AECO industry has been growing over the years [3,42], research indicates that BIM's full potential is yet to be fully achieved [63-65]. In the past, the lag in exploring the full potential of BIM applications was linked to several barriers [64], which include a lack of national standards, making it difficult to exchange data. Another barrier identified to have the most significant effect is the initial cost of implementation and the lack of experienced personnel. Organizational issues present another barrier, where upper management is sometimes reluctant to introduce new technologies due to fear of accountability and the extensive learning curve needed to adopt the technology [63-65]. Finally, the last barrier to efficient BIM adoption is legal issues of ownership and control over the data. It is worth mentioning that some countries, such as the United States and the United Kingdom, have made strides in creating BIM standards and have pushed to increase BIM adoption in the public and private sectors [64].

On the other hand, despite VR's long list of benefits to the AECO industry, its integration into the construction process has been slow [30,31]. One reason for the lag in adopting the new technology is the lack of research on its full potential to increase profits and efficiency versus its initial application cost [30,31]. Another limitation is the lack of expertise in employing VR in construction [17,30,31]. One notable issue with VR adoption is that some users experience motion-sickness due to the unnatural movement of "flying" or moving too fast (teleporting) in the VR environment [26]. The limitation can be countered by setting more realistic movement rules within the environment to avoid the issue.

Problem statement

MEP systems are a core component of any construction project, compromising about 40%-60% or more of the cost and work [12]. Also, those systems exist within confined and limited spaces; thus, they often cause clashes, errors, and inaccurate estimates. The construction process is susceptible to such issues, causing massive delays and cost overruns. As discussed in the literature review, while 3D BIM has the potential to assist in teaching MEP plan reading, BIM-VR has been selected as the preferred tool. The reasons for this choice are outlined below:

• Excellent enhancement of spatial understanding by immersion: While BIM alone offers 3D modeling, VR lets students interact with the model in an immersive, true-to-life environment. Such an experience may prove to be crucial in helping them make connections between 2D plan layouts and the actual, at times very complex, spatial configurations of MEP systems in structures. By "walking through" the MEP system in VR, students develop an intuition about what these systems look and feel like and how they fit within the physical space.

• Potential in improving spatial cognition skills such as clash detection: VR is not intended to identify clashes. There is specific clash detection software for that. The focus here is checking the improvement of spatial cognition using BIM, with clash detection as a task. In VR, students can view and detect these conflicts more realistically, as it provides spatial context that reveals issues like overlapping pipes or ducts in ways not as immediately obvious on a 3D screen or static BIM model.

• Reduced cognitive load compared to 3D BIM on screens: Immersion in VR can potentially reduce the cognitive load required to mentally convert 2D plans into spatial ideas. Students using non-immersive 3D-that is, standard BIM-must still create mental models of the spaces and often switch perspectives to understand complex layouts. This task becomes easier in VR because students can experience a model as much as they would in reality. This can potentially make the learning process smoother, more intuitive, and easier for students who have just begun to read MEP plans.

• An active and engaging learning experience: The interactivity and novelty of VR can potentially increase student engagement, which can positively impact learning outcomes. It may enhance retention and understanding of spatial relationships in the 2D plans, an advantage that standard 3D BIM viewing cannot provide. For more details about this discussion, refer to the questionnaire part of the study.

• Industry preparation for real-world scenarios: The combined solution using BIM-VR has become increasingly widely used in the industry, but it is still being used in developing BIM itself. Introducing VR aligns with industry trends.

To sum up, the BIM-VR application's effectiveness as an aid in interpreting and visualizing MEP components and systems should be explored.

There are scarce resources and studies on BIM-VR application within the context of MEP plan reading within the AECO education field. In the studies that attempted to evaluate its benefits or effectiveness, the results were mostly presented as a qualitative dataset of participants' "opinions" or "feedback." The limited research, mainly quantitative data, on the effectiveness of BIM-VR within the context of MEP plan reading education introduces a limitation to exploring its full potential [66].

Therefore, this study's main goal is to explore the full potential of BIM-VR in MEP plan reading learning. Through achieving said goal, the study objectives are as follows:

1. Comparing BIM-VR with traditional 2D teaching methods. This research will test whether BIM-VR can enhance the accuracy and efficiency of MEP plan reading within AECO classrooms compared to traditional 2D plan-based instruction.

2. Quantitative assessment of BIM-VR in MEP education. The study will use pre- and post-quizzes and structured questionnaire to quantitatively assess BIM-VR's impact on the learning experience, filling a void in the current literature primarily relying on qualitative assessments.

3. Promoting BIM-VR adoption in academia. The study aims to address the current lag in BIM-VR adoption within academia relative to industry practices. By illustrating the advantages of BIM-VR in enhancing MEP learning experiences, this research seeks to promote broader adoption of BIM-VR in educational settings.

4. Providing a quantitative dataset and roadmap for replication. This study will create a quantitative dataset that offers insights into BIM-VR's application within MEP systems. This dataset will serve as a foundation for further research. At the same time, the study's methodology can act as a roadmap for replicating similar experiments in various educational settings, facilitating wider academic adoption of BIM-VR technology.

5. Bridging the gap between industry practice and academic training. By addressing the gap in MEP-focused BIM-VR training, this study seeks to equip students and early-career professionals with the skills required to meet the complex demands of the AECO industry.

This research aims to bridge the divide between academic training and industry standards by empowering AECO students and young professionals to develop a more comprehensive understanding of MEP systems through BIM-VR technology.

Materials And Methods

The research framework (Figure 1) consisted of first conducting a literature review on the current application of BIM-VR in the AECO industry, focusing on education and MEP systems. The literature review served as the basis for optimizing the study parameters (details in "Step 1: study design" section). Next, the 3D and VR models were developed for a commercial building that was identified as an appropriate project for the evaluation process of the study after studying past case studies in the literature. The study participants were then determined based on the prerequisite of minimal BIM-VR experience and limited knowledge of MEP systems. Hence, a group of students from the Construction Engineering and Management program at the University of Delaware were selected. The study employed a randomized controlled trial design, randomly assigning participants to the control or test group. Pre-test and post-test measures were conducted to evaluate the comparative effectiveness of the intervention. Then, the data collection process started, where pre- and post-quiz scores were collected for each group, along with questionnaire responses about the learning experience. To ensure objectivity, both groups had identical conditions in which the quizzes were administered. Both had the same amount of time, used the same platform, and had the same questions, except where the test group had access to BIM-VR during the post-phase quiz. Finally, appropriate statistical methods for the study's purposes were identified, and results were reported.

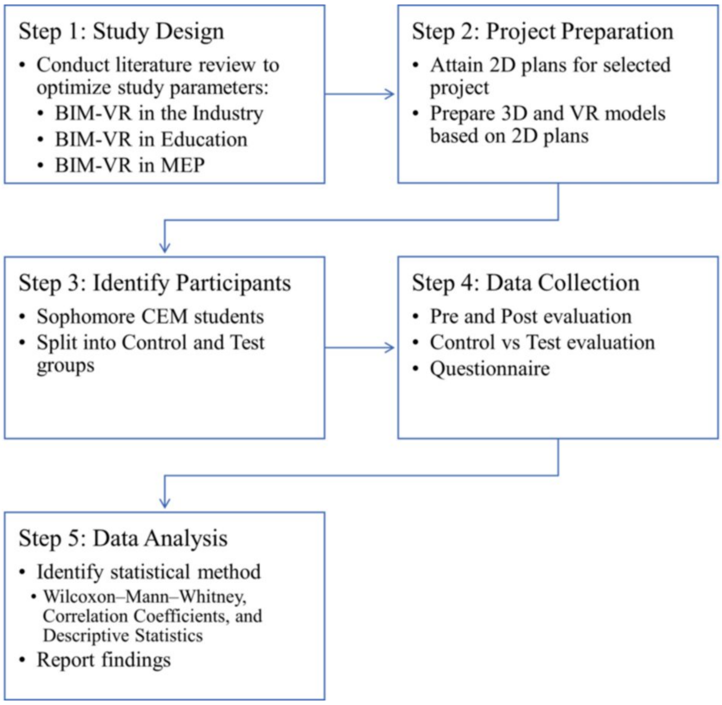

FIGURE 1: Research framework

MEP, Mechanical, Electrical, and Plumbing; BIM-VR, Building Information Modeling-Virtual Reality; CEM, Construction Engineering and Management

Step 1: study design

In order to optimize the parameters of this study, a comprehensive literature review was conducted. The literature review (refer to "Materials & Methods" section) included investigating case studies of BIM-VR applications within three categories. The first category investigated BIM-VR application in the AECO industry in general. The next investigated BIM-VR application within the AECO education field. The case studies explore how BIM, VR, or BIM-VR combined affect students' performance. The last category investigated BIM-VR application, specifically within MEP systems. The literature review researched industry- and education-based studies as well as applications of BIM, VR, or both BIM-VR combined. The purpose of segmenting the literature review into these categories was to comprehensively understand BIM-VR application within these different scenarios and the current status of said applications in AECO education and industry.

The following keywords were used when researching papers on BIM-VR applications for the varying contexts the study explored: BIM-VR in the AECO industry, BIM-VR in AECO education, and BIM-VR in MEP systems. The results were studied for other references until a sufficient dataset of papers was obtained.

A comprehensive literature review of the breadth of BIM-VR application, whether separate or combined, allows exploration of current research gaps in AECO education and industry. Several gaps have been noted in studies evaluating BIM-VR's effectiveness in MEP systems education. First, some studies overlooked the impact of the learning curve by using the same group for both evaluation phases-2D plans and BIM or BIM-VR applications-potentially skewing results [59]. Additionally, certain studies focused exclusively on BIM's 3D visualization capabilities without exploring the added benefits of VR's immersive environment [15]. Lastly, conflicting findings reported instances where groups using traditional 2D plans outperformed those using BIM-VR, highlighting the need for deeper investigation into BIM-VR's educational impact and effectiveness in classroom settings [60].

A better understanding of currently applied BIM-VR interventions and assessment methods enabled the authors of this study to optimize the proposed approach of BIM-VR teaching intervention. For instance, to minimize bias and provide a reliable basis for comparison, the study adopted a randomized controlled trial design instead of a single-group approach. The evaluation period was also condensed to 2 weeks, addressing potential learning curve effects that could skew results. The study also enhanced immersion by integrating a multi-layered BIM-VR experience, extending beyond basic BIM to examine the combined impact of BIM and VR on student performance.

Moreover, the literature review revealed conflicting findings regarding the effectiveness of BIM-VR in educational settings, underscoring the need for further investigation. Notably, there is a scarcity of studies employing quantitative assessment methods; therefore, this study incorporated a preliminary quantitative data analysis, moving beyond traditional qualitative assessments of student attitudes. Lastly, the study emphasized BIM-VR applications with a specific focus on MEP systems within classroom contexts, addressing a significant gap identified in the literature that academia lags behind industry in analyzing the effectiveness of BIM-VR.

Step 2: project preparation

This phase involved a few subtasks revolving around creating an evaluation process for the effectiveness of BIM-VR in enhancing comprehension of MEP plans within a classroom. The tasks included selecting a project, selecting appropriate software and equipment, and creating 3D and VR models.

Project Scope of Work

First, a project must be selected for the purposes of the study. Given that the purpose of the investigation is MEP-specific, a commercial project with detailed MEP work was deemed appropriate. Another criterion was selecting a project with a complete set of plans. The selection of a small commercial retail project as the basis for evaluation was driven by the participants' limited experience in plan reading, particularly in MEP plans. The full set of plans for the project was obtained. Autodesk Revit 2022 [67] was used to create a 3D model from the 2D plans. A Revit plugin (Enscape), a VR-friendly platform, was employed [68].

BIM and VR Model Development

All project components, whether architectural, structural, or MEP, were developed as BIM models in Autodesk Revit to match the 2D plans in specifications, dimensions, and properties as accurately as possible. The data included in the model are intended to be utilized by participants to perform tasks such as quality take-off, element identification, and dimension measurements in the BIM 3D environment. Therefore, the students were not required to create their own model; instead, they were provided access to the developed model for the purposes of this study. Furthermore, the MEP components were then color-coded in Enscape, a VR plugin for Revit by purpose. For instance, gas pipes were assigned the color black, while cold domestic water pipes were assigned blue. The objective was to provide distinctive visual properties of different components. The clear distinctions were designed to allow the participants to identify various parts and clashes among them more efficiently when viewing the 3D model. The combination of the BIM-VR approach was intended to allow students to interact with the project in various ways and environments, enhancing their learning experience and comprehension of MEP plan reading concepts such as quantity take-off in BIM and visualization of spatial conflicts in VR.

A list of the components versus the assigned color is listed below and illustrated in Figure *2*.

• Gas Pipes: Black

• Fire Protection Pipes: Orange

• Domestic Cold-Water Pipes: Blue

• Domestic Hot-Water Pipes: Red

• Sanitary Pipes: Light Green

• Supply Air Ducts: Aqua

• Return Air Ducts: Pink

• Exhaust Air Ducts: Light Green

VR goggles were used to have an immersive virtual experience of the model. Oculus Quest 2 is a user-and-cost-friendly VR goggle, has a high resolution of 1832 × 1920 pixels per eye, and is compatible with the selected software; thus, it was chosen for the study [69]. The Oculus Quest 2 was chosen based on hardware availability when the study was conducted. The required software and equipment were identified and prepared for the VR session for the participants. The Enscape plugin through Revit was employed to view the VR model through Steam VR. Figure 3 illustrates the VR model, VR goggles, and the participants interacting with the VR model.

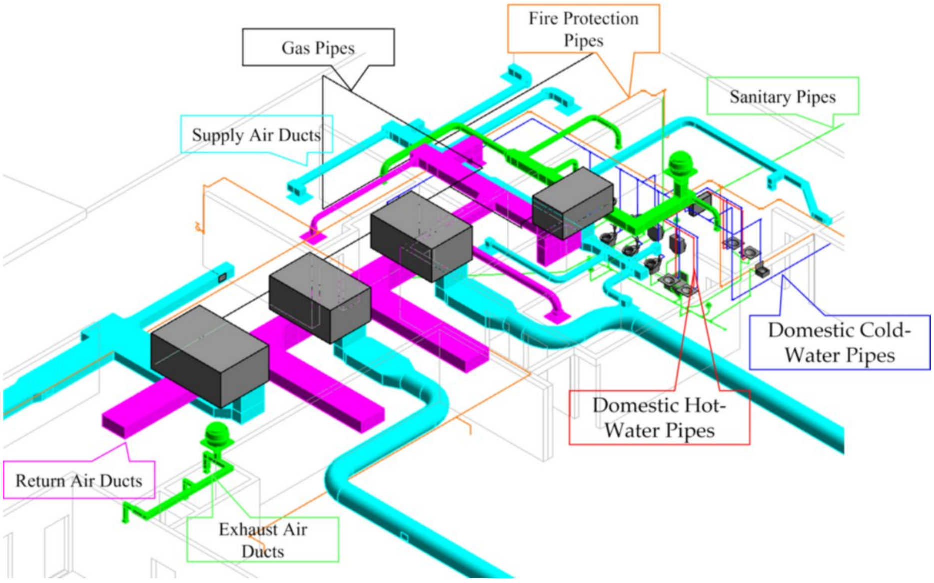

FIGURE 2: A visual sample of Revit 3D model

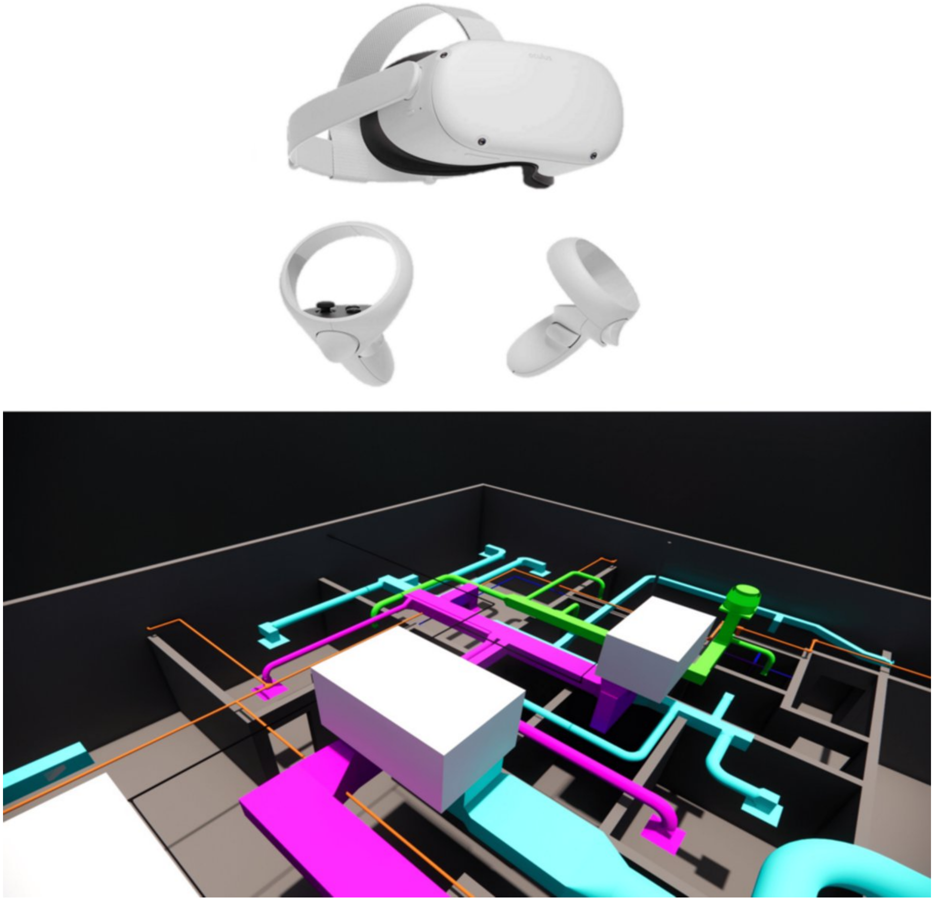

FIGURE 3: VR model, goggles, and participant VR interaction

VR, Virtual Reality

Step 3: identifying participants

After the evaluation model was created, participants in the study were selected. The investigation aimed to test the effectiveness of BIM-VR in the comprehension of MEP systems 2D plans. Hence, the participants were selected based on having minimal to no experience with BIM-VR, 2D plans, or MEP systems. The purpose was to eliminate the possibility of bias due to previous knowledge of the topic. Therefore, the participants were students in a second-year course in the Construction Engineering and Management (CEM) program at the University of Delaware. There were 21 participants divided into a control and test group, with more details about group demographics highlighted in Figure *4*. The control group was asked to complete the MEP systems plan reading tasks using only the 2D plans, while the test group had access to both the 3D and VR models during the evaluation process.

Note that the presented study is a pilot study with a relatively small sample size. Therefore, the study purposely adopted appropriate statistical methods capable of handling data with a small sample size. The selected tests include the Mann-Whitney U test and correlation coefficients visualization (refer to Step 5: data analysis, for details on each test). As a pilot, the study serves as an initial check, aiming to identify any promising trends in learning outcomes with BIM-VR. By leveraging these statistical tools, we were able to perform a quick, targeted assessment of BIM-VR's potential impact on spatial cognition and comprehension skills in MEP education. Hence, based on the selected statistical tests, a sample size of 21 will be sufficient to draw a meaningful statistical conclusion for the purposes of this preliminary pilot study.

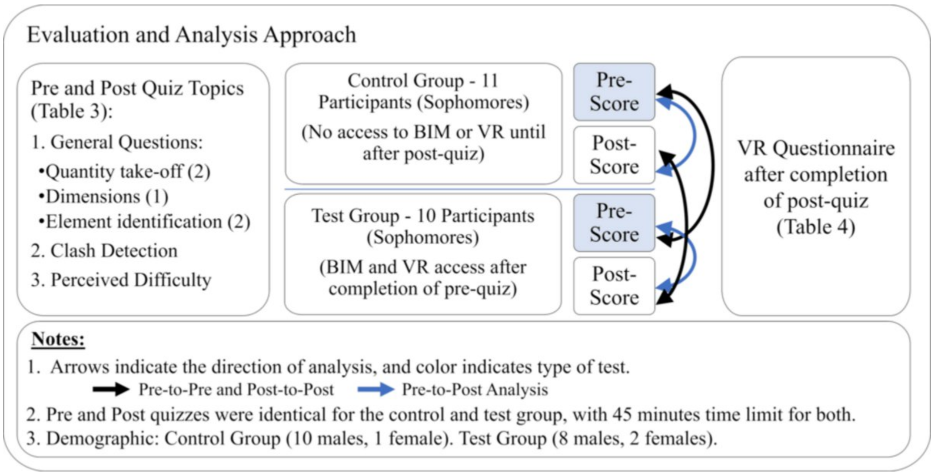

FIGURE 4: Evaluation and analysis approach

BIM, Building Information Modeling; VR, Virtual Reality

Step 4: data collection

The data collection process involved exploring options for a platform to deliver the information to the participants. Also, the assessment method was identified to facilitate appropriate data analysis of the BIM-VR effect on comprehension of MEP systems. The study was performed within 2 weeks at the beginning of the semester. The study's timeline was selected to minimize the possibility of a learning curve that could skew the data in favor of either BIM-VR or 2D.

The selected platform was the University's online education system for material sharing (Canvas). The delivery process started with providing the control and test group with the 2D plans to familiarize themselves over the first few days. Then, the assessment method was selected as pre-quiz and post-quiz to evaluate progress or lack thereof within and across both groups (Figure 4). Both groups would take the same quiz in the pre- and post-phase, with the difference of BIM-VR introduced to the test group during the post-phase.

The data collection process is outlined in Figure 5, highlighting the steps from the pre-quiz to the training sessions to the post-quiz and finally the questionnaire. The quizzes were administered online as multiple-choice questions during class time with a time limit of 45 minutes; the questions' content is detailed in Table 3. Both the pre- and post-quiz had a total of seven questions. The first five questions consisted of general questions covering element identification, dimension, and quantity take-off topics. The sixth question was directed toward error detection within the elements of the model. The participants were asked to identify project components with a clear violation of space constraints in which two elements occupied the same space. The students were asked to provide snapshots of the spatial conflict locations in the plans and describe the elements. The control group would provide snapshots of the 2D plans. In the case of the test group, they were able to provide snapshots from their VR walkthrough. They would then identify the conflict location in the plans. The intent was to evaluate students' ability to detect clashes to test their understanding of MEP plans. The final question asked the participants to determine the difficulty of the quiz on a Likert scale where 1 is very easy and 5 is very difficult (Figure 4).

The pre-quiz was administered under identical conditions for both groups. Both only had access to the project's 2D plans and were asked to focus on the MEP portion. After completing the pre-quiz, both groups received a training session on MEP systems and 2D plan reading. However, the test group had an added topic of BIM-VR, where they were briefly introduced to the software interface (Revit 2022). Next, the post-quiz would be administered. The control group was again only provided with the 2D plans along with a set of 2D plans generated from the 3D model. The added set of plans ensured that both groups had matching locations of clashes, thus allowing for the evaluation of clash detection using 2D plans versus 3D/VR. The test group was allowed access to the BIM and VR models during the post-phase.

Once this process ended and both groups completed the pre- and post-quiz, the control group was provided access to the BIM and VR models. The control group was given access to the BIM-VR models after completion of the post-quiz to ensure all students had an equal opportunity to develop the skills evaluated in this study. Both groups were asked to complete a Likert-scale questionnaire to evaluate their experience with BIM-VR application within MEP systems. Figure 4 highlights the evaluation process of the study for the pre- and post-quizzes of both groups. The questionnaire included a total of 11 questions highlighted in Table 4. The questionnaire was administered on the same platform online and outside class time.

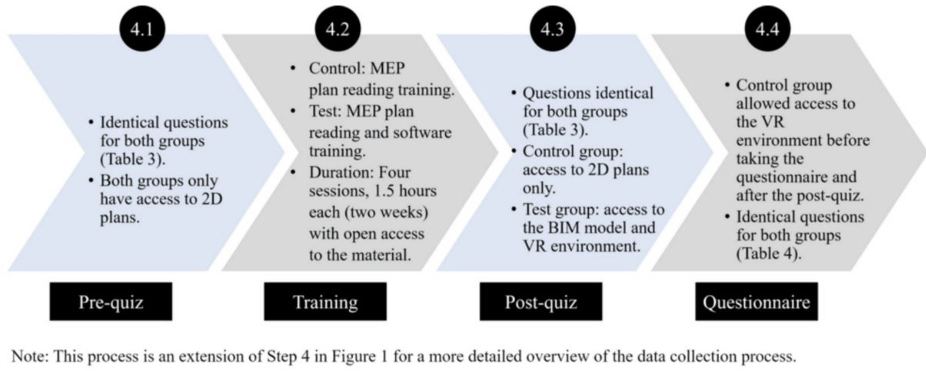

FIGURE 5: Data collection details

MEP, Mechanical, Electrical, and Plumbing; VR, Virtual Reality

Quiz	Question	Intent
Pre-Quiz	What are the diameters for the fire and domestic water pipes supplied to the building, respectively?	GQ: EI/D
	What are the count and diameters of the floor drains?	GQ: QT/D
	What is the estimated total surface area of the rectangular duct with the size of 46” × 16” in ft2?	GQ: QT
	What is the total number of supply air diffusers in this project?	GQ: EL/QT
	What are the supply air duct connection dimensions for RTU-1?	GQ: D
	Are there any clashes detected in the model? If so, please provide snapshots, along with brief descriptions and their specific locations.	CD
	What is the difficulty level of the questions?	PD
Post-Quiz	What is the total linear length of the domestic hot water pipes rounded up to the nearest inch?	GQ: QT
	What is the total number of both Tee and Elbow connections within the domestic cold-water pipes?	GQ: EI/QT
	List the types of pipes used in this project:	GQ: EI
	What is the linear length of all the ductwork pipes with a diameter of 18” rounded up to the nearest inch?	GQ: QT
	List the diameters of the round ducts in this project. What is their total area in ft2?	GQ: D
	Are there any clashes detected in the model? If so, please provide snapshots, along with brief descriptions and their specific locations.	CD
	What is the difficulty level of the questions?	PD

TABLE 3: Pre- and post-quiz questions

GQ, General Question; CD, Clash Detection; PD, Perceived Difficulty; EI, Element Identification; QT, Quantity take-off; D, Dimensions.

Q#	Question
Q1	I have extensive knowledge of the application of BIM-VR in MEP systems.
Q2	The use of VR helped improve my visualization of the MEP and HVAC systems.
Q3	The use of VR helped better understand and visualize MEP and HVAC connections.
Q4	The use of VR helped to easily detect errors and clashes in MEP and HVAC systems models.
Q5	The use of VR improved my comprehension and understanding of MEP and HVAC systems.
Q6	The use of VR aided in relatively reducing the complexity of identifying MEP and HVAC systems.
Q7	The use of VR increased information retention about MEP and HVAC systems.
Q8	The use of VR helped increase my confidence in MEP and HVAC systems comprehension.
Q9	The use of VR significantly increased my motivation to learn more about MEP and HVAC systems.
Q10	The use of VR relatively mimicked the real-life experience of a site.
Q11	The use of BIM-VR was overall a positive learning experience.

TABLE 4: Questionnaire list of questions

MEP, Mechanical, Electrical, and Plumbing; BIM-VR, Building Information Modeling-Virtual Reality; HVAC, heating, ventilation, and air conditioning

Step 5: data analysis

The analysis process was carried out in stages. The first stage was comparing the pre- and post-test results within each group independently. Next, the control group's results were analyzed through pre-to-pre and post-to-post comparison to the test group's results. The final phase consisted of analyzing the Likert-scale questionnaire provided to both groups. The stages of analysis were developed to study the impact of BIM/VR applications on the learning experience of MEP systems.

The experiment results were analyzed through several statistical approaches. The statistical methods applied include descriptive statistics, boxplots, Mann-Whitney U test, and correlation coefficients. The analysis was done within and across the groups to evaluate BIM-VR's effect on the MEP plan reading learning experience. Next was analyzing the questionnaire results, which included a graphical representation and descriptive statistics for each question. Figure *4* illustrates a graphical representation of the direction and process of the analysis. The significance level throughout the analysis will be considered as 0.05.

Descriptive Statistics and Boxplots

The descriptive statistics section provides a comprehensive summary of the dataset. Measures of central tendency, such as the mean, median, and mode, are presented to offer insight into the typical or central values of the data. Additionally, measures of dispersion, including range and standard deviation, are included to elucidate the spread or variability of the data points. Furthermore, boxplots are illustrated to highlight critical components such as the median, quartiles, and whiskers, providing insights into the distribution of the data and any notable patterns observed. Boxplots were selected to better visualize data distribution and are suitable for datasets as small as $n = 5$ [70,71]. This comprehensive overview enhances the readers' understanding of the dataset and its properties, laying the groundwork for further analysis and interpretation.

Mann-Whitney U Test

The analysis employed a strategic use of the Mann-Whitney U test, a robust non-parametric test capable of handling non-normally distributed data with a limited sample size [72,73]. The Mann-Whitney U test involves combining the data of both samples, which, in this case, are referred to as groups (control and test), and then the combined observations are ranked. Next, the groups are separated again with their associated ranks. The goal is to test if the groups are similar to each other (Ho) or alternatively significantly differ from each other (Ha), where one group is either significantly higher or lower in rank [72,73]. The sample size in this study is 21, with 11 students in the control group and 10 in the test group. Therefore, the Mann-Whitney U test was used as it is appropriate for the purpose of the proposed pilot study.

The primary objective was to evaluate if there were significant changes in performance from pre-to-post within each group and pre-to-pre or post-to-post across groups to assess the influence of BIM-VR intervention on the MEP plan reading learning experience. Notably, the control group had no access to BIM until after the post-quiz, while the test group utilized BIM during the post-quiz phase. Consequently, the Mann-Whitney U test can provide valuable insights into performance differences when conventional 2D plans were used (Control Group) versus BIM-VR intervention (Test Group).

Correlation Coefficients

Correlation coefficients range from −1 to 1, where −1 indicates a perfect negative relationship while 1 is a perfect positive relationship. Therefore, the closer a value is to 0, the weaker the correlation between the two analyzed variables [74]. In stages one and two, correlation coefficients were strategically employed alongside Mann-Whitney U tests to provide deeper insights into the impact of the BIM-VR intervention when compared to traditional teaching methods employing 2D plans for MEP plan reading comprehension. In stage one, correlation coefficients were utilized to examine the relationship between pre-to-post-intervention performance within each group. This approach allowed for a better understanding of how participants' performance changed over time to further understand the effectiveness of the BIM-VR intervention compared to traditional 2D plans.

Additionally, in stage two, correlation coefficients were applied to explore the consistency of performance levels over time across both groups. By comparing pre-to-pre and post-to-post scores between groups, this analysis provided valuable insights into the changes in performance and the effects of the BIM-VR intervention. Understanding the correlation relationships in both stages not only elucidated the magnitude of performance changes but also revealed the direction of the relationship, whether positive or negative, which offered more profound insights into the influence of the BIM-VR intervention on the learning experience. This comprehensive analysis, integrating correlation coefficients with Mann-Whitney U tests, can provide a robust evaluation of the intervention's efficacy and a more holistic understanding of its impact on MEP plan reading comprehension.

Results

The results section will aim to evaluate the effectiveness of the proposed approach. The evaluation will be achieved by comparing pre- and post-quiz scores within and between groups. The comparison will aid in evaluating the effect BIM-VR has on MEP plan reading comprehension and performance. Therefore, the control group will first be assessed to determine if performance could be improved when only 2D plans were provided between pre- and post-quiz phase. Then, the test group's performance will be similarly evaluated to further understand BIM-VR's influence on their performance. Next, both groups will be compared to each other to add an additional layer of analysis where it will be investigated if the test group had a significant improvement in performance when BIM-VR was provided compared to the control group with strictly 2D plans in the post-phase. On the other hand, the pre-phase will serve as the baseline for performance, ensuring both groups are on the same level before starting the investigation. Finally, the questionnaire took place after the post-phase of the quizzes was completed, and the control group was provided access to the BIM-VR application. Both groups were then required to complete the questionnaire. The results will be evaluated to explore participants' attitudes toward using BIM-VR to improve MEP plan reading comprehension.

Control group

As previously highlighted, the control group had no access to the 3D or VR models until the end of both pre- and post-phases of the experiment. Withholding BIM-VR access from the control group serves as a baseline for performance when using 2D plans only. The baseline allows for comparison with the test group to further understand the effect of BIM-VR on MEP plan reading skills. The statistical tests applied were summary statistics, paired Mann-Whitney U, and correlation coefficients.

Descriptive Statistics

Descriptive statistics of the control group data are presented in Table *5* and Figure *6*. Although the test group's pre-quiz scores appear slightly higher than those of the control group, statistical analysis under the "Combined control versus test" section indicates that the difference is not statistically significant. This suggests that both groups had relatively similar performance levels before the intervention. Next, the test group's scores show a substantial increase in mean scores of the general questions and clash detection portions. Clash detection mean scores were again zero for the pre-quiz phase for the same reasons explained under the control group. However, when participants were provided with BIM-VR access, their ability to identify clash areas increased to 66% compared to the 10% of the control group. Figure *9* illustrates sample snapshots provided by the test group participants, highlighting spatial conflict locations throughout the project. Furthermore, the mean score of perceived difficulty decreased from 3.78 to 2.60. The noticeable decrease indicates that participants perceived the post-quiz as easier than the pre-quiz when BIM-VR was introduced. The results are further proved by the control group, which showed no progress between the two phases of pre-to-post. The standard deviation of scores decreased in the post-phase of the general questions, implying less variability, perhaps due to enhanced performance. On the other hand, the standard deviation of the clash detection in the post-phase is relatively high, showing a significant variability in the data. The variability is also highlighted in the range of 90. The reason behind the variability might be that clash detection was still a new concept to the participants. While BIM-VR significantly helped some, others struggled to comprehend the notion of clash detection. Finally, the standard deviation in the perceived difficulty portion increased, suggesting less agreement, but is still relatively low.

Phase	Pre-Phase			Post-Phase		
Parameter	GQ (%)	CD (%)	PD (5-point Likert scale)	GQ (%)	CD (%)	PD (5-point Likert scale)
Mean	27.27	0	3.91	24.55	10.00	4.50
Median	33.33	0	4.00	16.67	10.00	5.00
Range	66.67	0	3.00	39.17	25.00	2.00
Standard Deviation	20.10	-	0.94	14.65	9.75	0.71

TABLE 5: Control group descriptive statistics

GQ: General Questions; CD: Clash Detection; PD: Perceived Difficulty

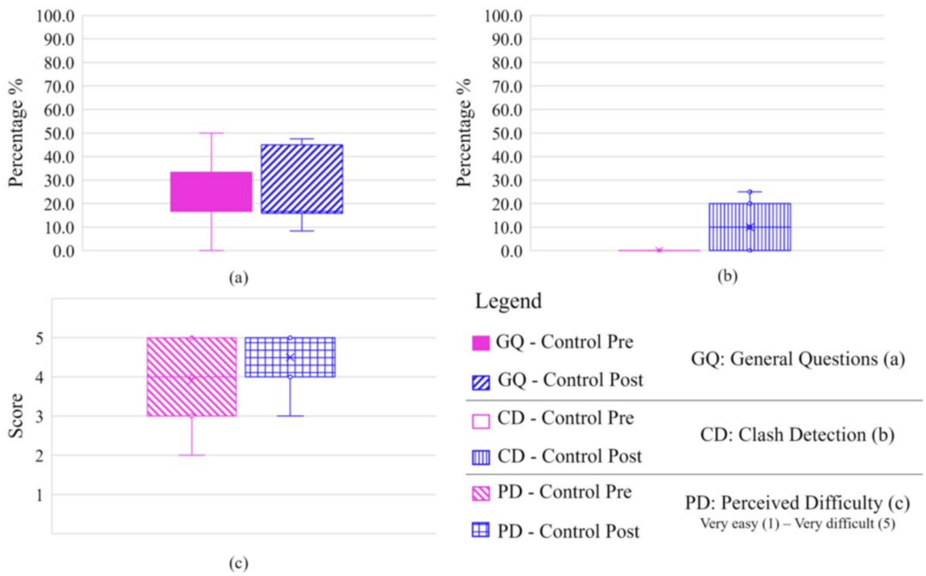

FIGURE 6: Control group box plots, where (a) general questions, (b) clash detection, and (c) perceived difficulty

GQ: General Question, CD: Clash Detection, PD: perceived Difficulty

Mann-Whitney U Test

The pre-to-post scores of the general questions, clash detection, and perceived difficulty were analyzed. Table 6 highlights the results of the test. The pre-to-post score results for the general questions portion were not statistically significant (Table 6). Therefore, this indicates no improvement in scores when using 2D plans for MEP systems; as for the clash detection portion, the Mann-Whitney U test shows statistically significant and demonstrates an improvement from the pre-phase. However, as previously noted, a 10% score average for clash detection is still considered poor performance. Finally, the perceived difficulty appears significant, explicitly showing a substantial increase in the mean. Therefore, this again indicates that despite being provided with a training session, the control group still perceived the given task of MEP plan reading to be difficult.

Parameter	GQ (%)	CD (%)	PD (5-point Likert scale)
Mean Difference	−2.72	10	0.59
N	11	11	11
S**	126.5	165.0	130.5
Expected Score	126.5	126.5	126.5
Prob ≤ S	0.330	0.0019*	0.080
Prob ≥ |S-Mean|	0.660	0.0039*	0.138

TABLE 6: Control group paired Mann-Whitney U results

* Statistically significant.

** S: The sum of the rank scores for the observations in the smaller group.

GQ: General Questions; CD: Clash Detection; PD: Perceived Difficulty

Correlation Coefficients

Correlation coefficients were produced to further understand the relationship between the scores through the pre-to-post phase of the control group. Figure 7 illustrates the relationship between pre-to-post scores of all three categories. The correlation figures confirm there is no correlation between pre-to-post scores of the general questions portion (Figure 7a). There is a moderately strong correlation between pre-to-post clash detection scores (Figure 7b), yet the average is still significantly low (10%). Finally, a moderate positive correlation in perceived difficulty indicates that the score increased but not drastically (Figure 7c).

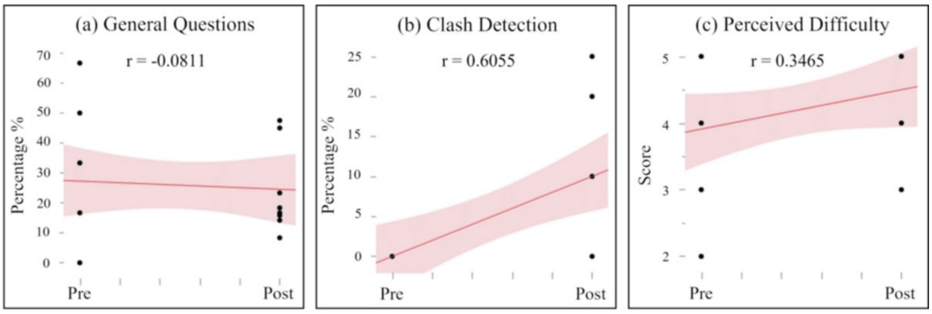

FIGURE 7: Control group pre-to-post correlation coefficients, where (a) is general questions, (b) is clash detection, and (c) is received difficulty

Test group

The test group's results were analyzed similarly to those of the control group using descriptive statistics and Mann-Whitney U tests. As previously noted, during the post-quiz phase, the test group was granted access to the BIM-VR models. Therefore, this enabled the authors to evaluate if any score improvement occurred with BIM-VR intervention.

Descriptive Statistics

Descriptive statistics of the test group data are presented in Table 7 and Figure 8. While the test group's pre-quiz scores appear to be relatively higher than the control group, statistical analysis of the pre-quiz results in section (4.3) are not statistically significant, indicating their performance was relatively similar. Next, the test group's scores show a substantial increase in mean scores of the general questions and clash detection portions. Clash detection mean scores were again zero for the pre-quiz phase for the same reasons explained under the control group. However, when participants were provided with BIM-VR access, their ability to identify clash areas increased to 66% compared to the 10% of the control group. Figure 9 illustrates sample snapshots provided by the test group participants, highlighting spatial conflict locations throughout the project. Furthermore, the mean score of perceived difficulty decreased from 3.78 to 2.60. The noticeable decrease indicates that participants perceived the post-quiz as easier than the pre-quiz when BIM-VR was introduced. The results are further proved by the control group, which showed no progress between the two phases of pre-to-post. The standard deviation of scores decreased in the post-phase of the general questions, implying less variability, perhaps due to enhanced performance. On the other hand, the standard deviation of the clash detection in the post-phase is relatively high, showing a significant variability in the data. The variability is also highlighted in the range of 90. The reason behind the variability might be that clash detection was still a new concept to the participants. While BIM-VR significantly helped some, others struggled to comprehend the notion of clash detection. Finally, the standard deviation in the perceived difficulty portion increased, suggesting less agreement, but is still relatively low.

Phase	Pre-Phase			Post-Phase		
Parameter	GQ (%)	CD (%)	PD (5-point Likert scale)	GQ (%)	CD (%)	PD (5-point Likert scale)
Mean	40.00	0	3.78	81.00	66.00	2.60
Median	41.67	0	4.00	81.25	62.50	3.00
Range	66.67	0	1.00	45.83	90.00	3.00
Standard Deviation	21.08	-	0.44	15.65	33.81	0.84

TABLE 7: Test group descriptive statistics

GQ: General Questions; CD: Clash Detection; PD: Perceived Difficulty.

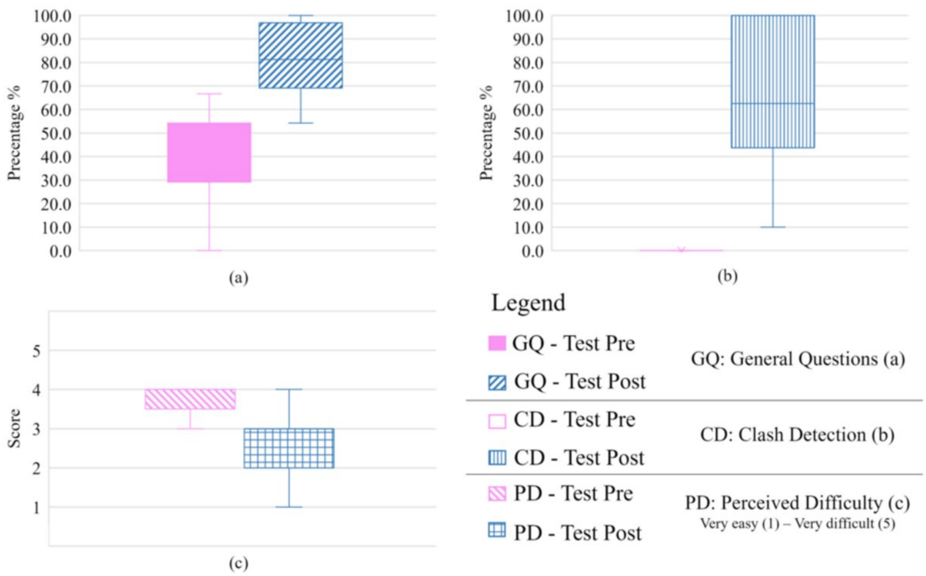

FIGURE 8: Test group box plots, where (a) general questions, (b) clash detection, and (c) perceived difficulty

GQ: General Question, CD: Clash Detection, PD: Perceived Difficulty

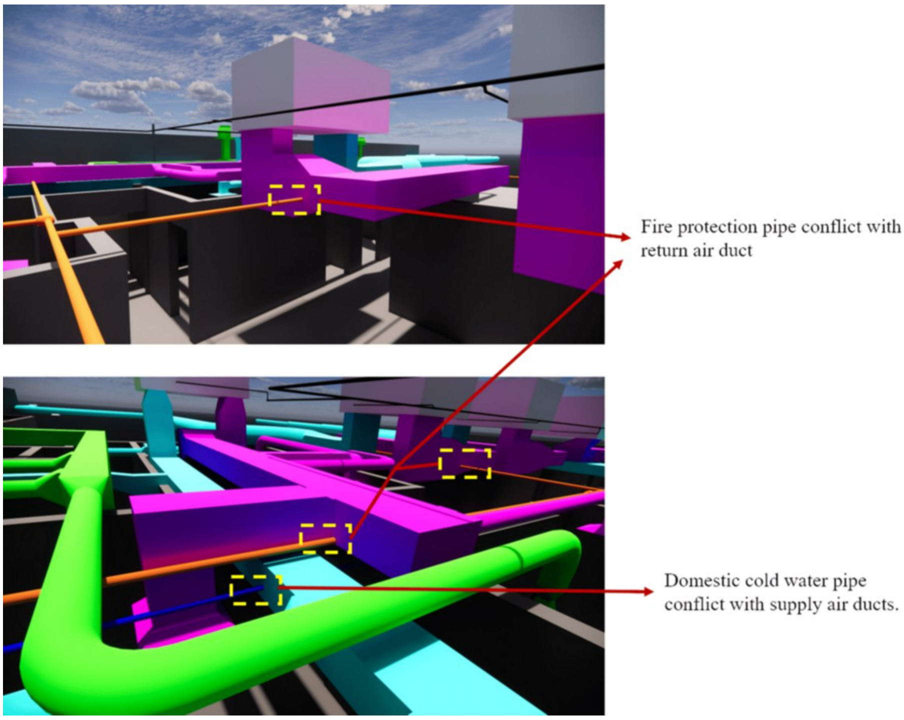

FIGURE 9: Clash detection sample snapshots in the VR environment (test-group students)

VR, Virtual Reality

Mann-Whitney U Test

The pre-to-post scores of the general questions, clash detection, and perceived difficulty were analyzed, as highlighted in Table 8. First, looking into the general questions portion, the results are statistically significant and imply an increase in the mean scores. Hence, when the BIM-VR application was introduced, their performance was enhanced by roughly 41% from pre-to-post. Similar conclusions can be drawn for the clash detection portion, which is statistically significant, with an increase of 66%. Finally, there is a statistically significant decrease of 1.18 points on a scale of 1 to 5 for the perceived difficulty portion. The reduction shows that the participants viewed the post-quiz as more manageable than the pre-quiz when BIM-VR was available. The combined results of all three portions indicate that performance is significantly improved when BIM-VR is introduced to aid in the comprehension of MEP plan reading.

Parameter	GQ (%)	CD (%)	PD (5-point Likert scale)
Mean Difference	41.00	66.00	−1.18
N	10	10	10
S**	151.00	155.00	124.50
Expected Score	105.00	105.00	105.00
Prob ≤ S	<0.0001>	<0.0001>	0.0019*
Prob ≥ |S-Mean|	<0.0001>	<0.0001>	0.0024*

TABLE 8: Test group Mann-Whitney U results

* Statistically significant.

** S: The sum of the rank scores for the observations in the smaller group.

GQ: General Questions; CD: Clash Detection; PD: Perceived Difficulty.

Correlation Coefficients

Correlation coefficients were produced to further understand the relationship between the scores through the pre-to-post phase of the test group illustrated in Figure *10*. The general question (Figure *10a*) and clash detection (Figure *10b*) portions show a robust positive relationship between the pre-to-post phase. The positive relationship implies a considerable increase in scores linked to the presence of BIM-VR in the post-phase compared to the lack thereof in the pre-phase. Finally, a moderately strong negative relationship exists in perceived difficulty (Figure *10c*) between the pre-to-post phase. The negative relationship again highlights that MEP plan reading becomes a more manageable task when BIM-VR is available to participants.

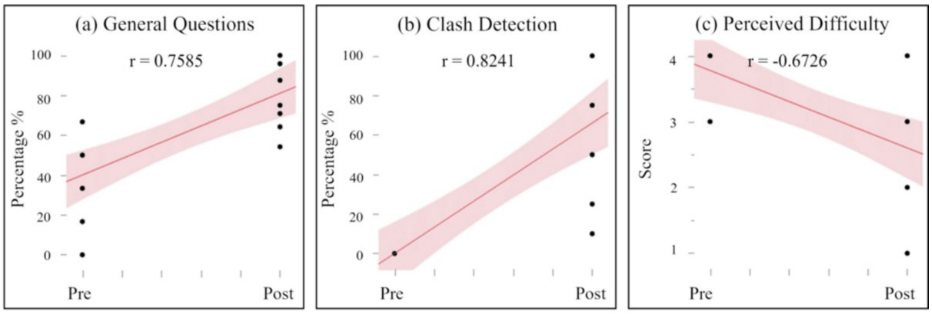

FIGURE 10: . Test group pre-to-post correlation coefficients, where (a) is general questions, (b) is clash detection, and (c) is received difficulty

Combined control versus test

After completing the separate analysis of each group, the next step is to study the results across the groups. Figure *11* highlights the relationship between the two groups' pre-to-pre-phase and post-to-post-phase performance. As highlighted in the next section, the results seem relatively similar for both groups when looking at the pre-phase of all three categories with no statistical significance. On the other hand, the test group's performance significantly increased compared to the control group in the post-phase. The increase was highlighted under the general questions and clash detection portions. As for the perceived difficulty, there is a substantial decrease in the post-phase of the test group compared to the control group. Next, similar approaches and tests were conducted to analyze the relationship of BIM-VR on MEP plan reading comprehension for control versus test groups. Mann-Whitney U test was used. Finally, correlation figures and coefficients are discussed.

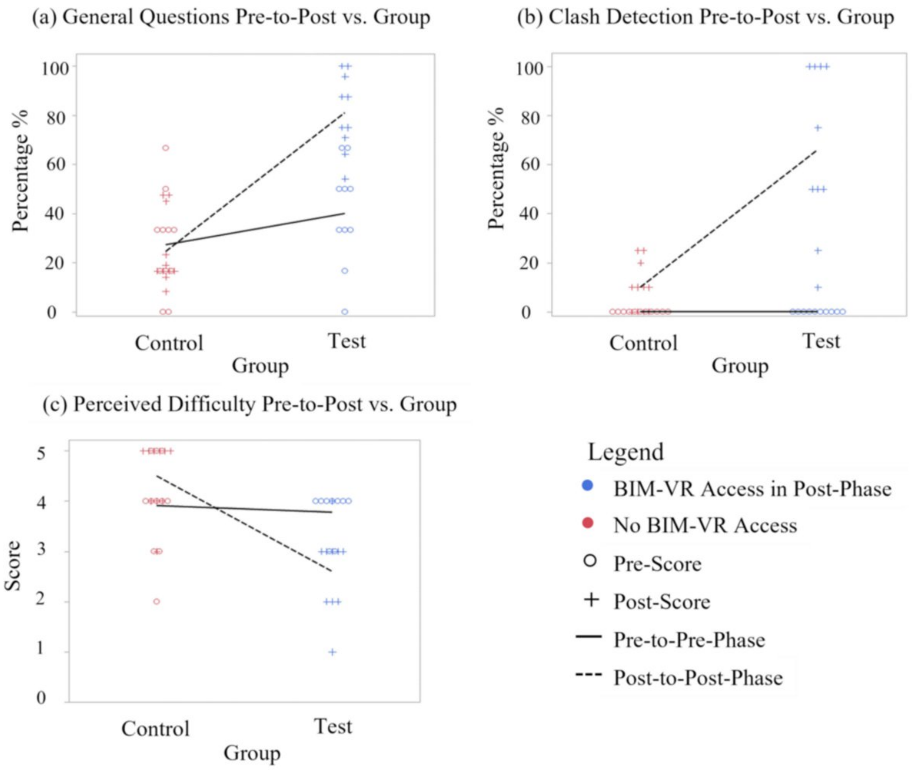

FIGURE 11: Relationship between control and test group pre-to-post, where (a) is general questions, (b) is clash detection, and (c) is received difficulty

BIM-VR, Building Information Modeling-Virtual Reality

Mann-Whitney U test

The Mann-Whitney U test results are displayed in Table 9. The three categories were analyzed across both groups of pre-to-pre and post-to-post analysis. The three categories are statistically insignificant in the pre-to-pre analysis. Those results are to be expected, as the conditions of the pre-phase were identical for both groups. Neither group was provided BIM-VR access during the pre-quiz and has not had a training session yet.

On the other hand, all three categories show statistical significance in the post-to-post analysis. The general questions portion shows a mean difference of 56.45 from the test to the control group. Also, the Mann-Whitney U test shows a significant increase in the test group's scores versus the control group. The clash detection portion is similar to the general questions, with a mean difference of 56.00 and indicating significantly higher scores for the test group versus the control group. Finally, the perceived difficulty portion has a mean difference of −1.90, highlighting that the test group perceived the questions to be easier despite being identical to the control group. The Mann-Whitney U test shows a significant decrease in the perceived difficulty of the test group versus the control group.

Phase	Pre-to-Pre			Post-to-Post		
Parameter	GQ (%)	CD (%)	PD (5-point Likert scale)	GQ (%)	CD (%)	PD (5-point Likert scale)
Mean Difference	41.00	66.00	−1.18	41.00	66.00	−1.18
N	10	10	10	10	10	10
S**	151.00	155.00	124.50	151.00	155.00	124.50
Expected Score	105.00	105.00	105.00	105.00	105.00	105.00
Prob ≤ S	<0.0001>	<0.0001>	0.0019*	<0.0001>	<0.0001>	0.0019*
Prob ≥ |S-Mean|	<0.0001>	<0.0001>	0.0024*	<0.0001>	<0.0001>	0.0024*

TABLE 9: Combined control and test group Mann-Whitney U test analysis

* Statistically significant.

** S: The sum of the rank scores for the observations in the smaller group.

GQ: General Questions; CD: Clash Detection; PD: Perceived Difficulty.

Correlation Coefficients

First, starting with the pre-to-pre results, no strong correlations within any categories are illustrated in Figure *12a*, Figure *12b*, and Figure *12c*. The lack of relationship is attributed to the fact that both groups had identical conditions and thus should have similar performance. In the clash detection portion, the correlation coefficient appears zero due to the participants' inability to answer the question during the pre-phase. Next, in the post-to-post phase, there are strong correlations of enhanced performance when BIM-VR was introduced to aid MEP plan reading. The general questions (Figure *12d*) and clash detection (Figure *12e*) show strong positive correlations, thus indicating significantly increased scores on the quiz for both portions. Meanwhile, the perceived difficulty portion (Figure *12f*) shows a strong negative correlation between the control and test groups. Thus, when BIM-VR was introduced to aid MEP plan reading, the task was perceived to be more manageable than only 2D plans.

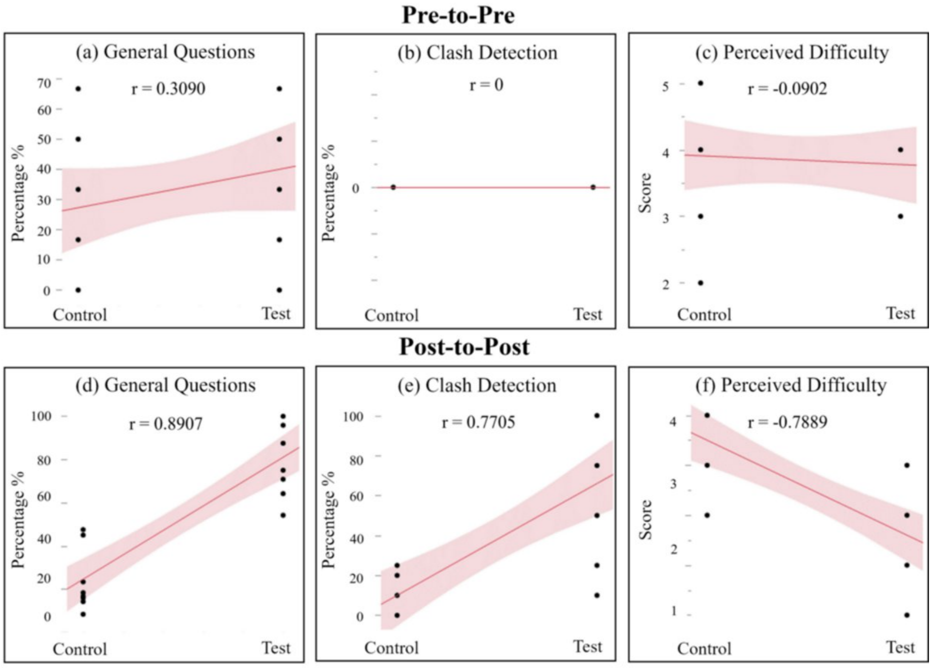

FIGURE 12: Combined pre-to-pre and post-to-post correlation of control vs. test group, where (a) is pre-to-pre general questions, (b) is pre-to-pre clash detection, (c) is pre-to-pre received difficulty, (d) is post-to-post general questions, (e) is post-to-post clash detection, (f) is post-to-post received difficulty.

Questionnaire

At the end of the study, both groups were asked to answer a five-point Likert-scale questionnaire ranging from strongly disagree to strongly agree (Table 4). When analyzed, the responses of both groups proved to be very similar, and no significant difference was found. As previously detailed, the test group was provided BIM-VR access during the post-phase, while the control group gained access after the post-phase was completed to understand their attitudes further and ensure they had access to the same learning experience as the test group. Figure 13 illustrates the results of the questionnaire for both groups. The results were analyzed through mode, mean, and standard deviation. The standard deviation varied from 0.4 to 0.91, while the mode was 4 or 5 for most questions. The only exception is Q1, which evaluated the participants' experience with BIM-VR applications in MEP plan reading with a mode of 2.

The results of Q1 reiterate the previously stated proposition that the participants were selected based on having minimal to no experience with BIM-VR in MEP plan reading. The other questions were ranked based on the mean of the scores, where all questions were considered to carry the same weight. The top criterion per the participants' experience was (Q2) enhanced visualization of MEP systems when using BIM-VR. The following two categories were efficient error detection (Q4) and creating a positive learning environment (Q11), ranking second and third, respectively. The mean for all questions, excluding the prior experience one, range between 3.86 and 4.81, indicating a positive perception of BIM-VR implementation to enhance comprehension of MEP plan reading.

When observing the results of the questionnaire along with the post-quiz results pertaining to the clash detection portion, VR played a significant role in improving students' learning experience when it came to MEP plan reading. Mainly, VR contributed to improving the following:

• Improved student (test group) ability to detect spatial conflicts despite minimal exposure to clash detection concepts. This is highlighted from the pre- and post-quiz analysis for each group as well as Q4 in the questionnaire.

• Improved visualization of MEP systems (Q2), as previously highlighted by the questionnaire results.

• Improved learning experience by enhancing students' comprehension of MEP systems (Q3, Q5, Q6-Q8), increasing motivation to learn (Q9), and fostering a positive learning experience (Q11). Also, VR enabled students to have relatively realistic experiences on a site, which is valuable for preparing students for their future careers (Q10).

Therefore, the immersive VR environment is a valuable asset to students in the AECO classroom, as it fosters a positive learning environment, allowing access to aspects of learning not available in traditional teaching modes. It goes beyond the 3D visualization of BIM through immersion and mimicking real-life site experiences.

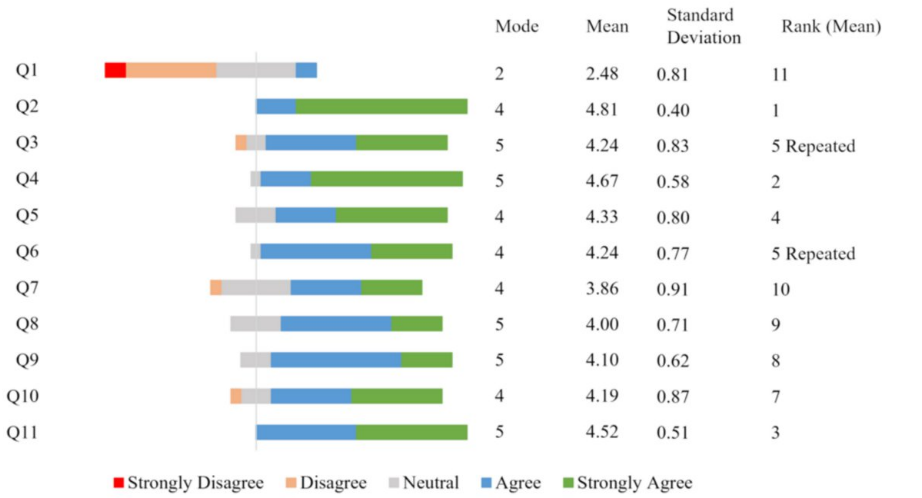

FIGURE 13: Questionnaire results

Discussion

To fully understand the influence of BIM-VR on learning, Bloom's Taxonomy was explored in many studies evaluating BIM-VR's influence in the classroom [46,75,76]. Bloom's Taxonomy offers deeper insights into how BIM-VR enhances the learning experience beyond measuring performance and feedback. It serves as a valuable evaluation framework to critically assess the learning outcomes achieved through BIM-VR. This approach provides educators with essential guidance to optimize BIM-VR use in the classroom, ensuring that learning objectives at all cognitive levels are effectively addressed.

BIM-VR touches on all levels of cognitive thinking identified in Bloom's Taxonomy (Figure *14*): Remember, Understand, Apply, Analyze, Evaluate, and Create [46,75,76].

• Enhanced visualization and immersive environments provided by BIM-VR have been shown to significantly boost students' ability to retain information, supporting foundational knowledge recall (level 1).

• BIM-VR also strengthens students' understanding of complex concepts by enabling immersive exploration of projects. This interactive experience allows them to navigate and engage with project components in a way that surpasses traditional 2D plans (level 2).

• With improved memory retention and comprehension of plan-reading concepts using BIM-VR, students are better equipped to apply their knowledge in problem-solving scenarios (level 3).

• This foundational understanding empowers students to analyze information critically, draw conclusions, and identify relationships between different project components, further developing their analytical skills (level 4).

• At the evaluation level, students can assess project content more effectively, making informed judgments and thoughtful decisions on possible improvements, reinforcing their ability to critically evaluate and refine designs (level 5).

• Finally, BIM-VR empowers students to reach the highest level of Bloom's Taxonomy: creation. By synthesizing their knowledge and insights gained through immersive experiences, they can design, reconfigure, or even innovate solutions within the project context, fostering creativity and deeper engagement with construction planning and execution (level 6).

Figure 14 illustrates how each level of Bloom's Taxonomy would be achieved within the specific context of BIM-VR application in this study and relates them to the questionnaire results from Table 4 and Figure 13.

The control group in this study utilizing 2D plans struggled to achieve Levels one through four, which is this study's focus. Their struggle with the tasks was reflected in their relatively poor performance compared to the test groups. This study did not expand into the last two levels, as they require advanced cognition, which would be difficult to develop within the limited timeframe designated for this study. However, the test group outperformed the control when BIM-VR was introduced. Relating that to the improved visualization aspect reported by the students, having a higher level of detail by visualizing the project components, materials, dimensions, and space constraints, the students were able to better remember and understand the different types of elements and identify them. Also, they were able to apply the knowledge to perform tasks such as quantity take-off and measuring dimensions. Lastly, they were able to analyze the model and identify spatial conflicts between clashing elements.

The results of the control, test, and combined groups paint a complete picture of the impact of BIM-VR application on MEP plan reading comprehension. The control group showed no improvement from pre-to-post in the general questions and even perceived the questions to be more difficult in the second round. As for clash detection, while improved, it was still below the acceptable performance of identifying clashes. The correlation figures showed that the control group struggled to complete the required tasks from pre-to-post, depending on MEP plan reading comprehension. Therefore, this indicates that the traditional instruction mode is ineffective at improving students' comprehension of MEP plan reading.

The test group's results indicate enhanced performance on all ends, a significant increase in the general questions and clash detection portion, and the participants perceived the process to be much less complex when BIM-VR was provided. The correlation figures highlighted the relationship between BIM-VR application and enhanced MEP plan reading abilities. In contrast to the traditional 2D plans approach, BIM-VR enabled students to better grasp MEP plan reading concepts by enhancing visualization. That is evident in their performance compared to the control group, which showed no improvement. The results support the proposed hypothesis that BIM-VR can be an effective learning tool.

When studying the combination of both groups, there was no difference in the pre-to-pre phase, as both groups had identical conditions. However, the post-to-post analysis shows a clear difference, with the test group performing significantly better on all ends. The relationship between pre-to-pre and post-to-post across the control and test groups was evaluated through correlation figures of each category. The results highlighted the significant improvement of the test group in the post-phase with BIM-VR access compared to the control group with no access. The results of comparing groups to each other using the statistical tests all indicate that the students with BIM-VR access significantly outperformed students without access, further highlighting the benefits of BIM-VR intervention in improving participants' comprehension of MEP plan reading skills. Finally, when studying the Likert-scale questionnaire results where the control group was given access to BIM-VR as well, after completing the post-quiz, the test and control group similarly rated BIM-VR benefits. The results imply that according to the participants' experience, BIM-VR enhanced visualization and allowed efficient error detection. Also, the students had a positive attitude toward the learning experience, which was evaluated through Conformity Factor Analysis.

The results of all the analyses indicate that BIM-VR intervention to enhance MEP plan reading skills is a much more effective approach than the traditional 2D plan mode of instruction. Also, the results show that students' motivation increased when BIM-VR was introduced, proving a positive learning experience. Therefore, academia should push toward increasing BIM-VR adoption for MEP plan reading and other AECO-related tasks where possible to better prepare students and young professionals for the AECO industry demands by providing them with the necessary skills to succeed. Hence, a detailed implementation map was developed as a result of this study to enable replication in other settings to capitalize on the listed BIM-VR advantages in this study, illustrated in Figure 15.

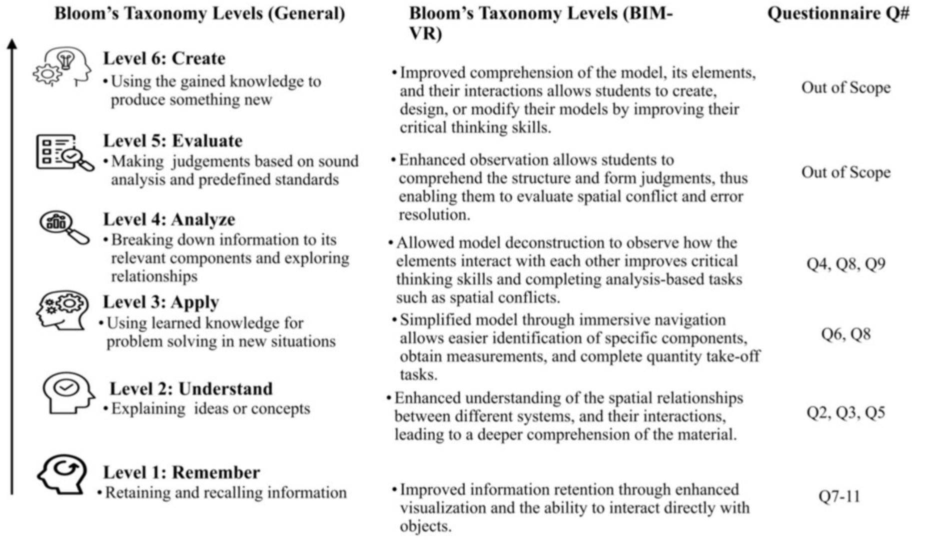

FIGURE 14: Bloom's Taxonomy in relation to BIM-VR utilization

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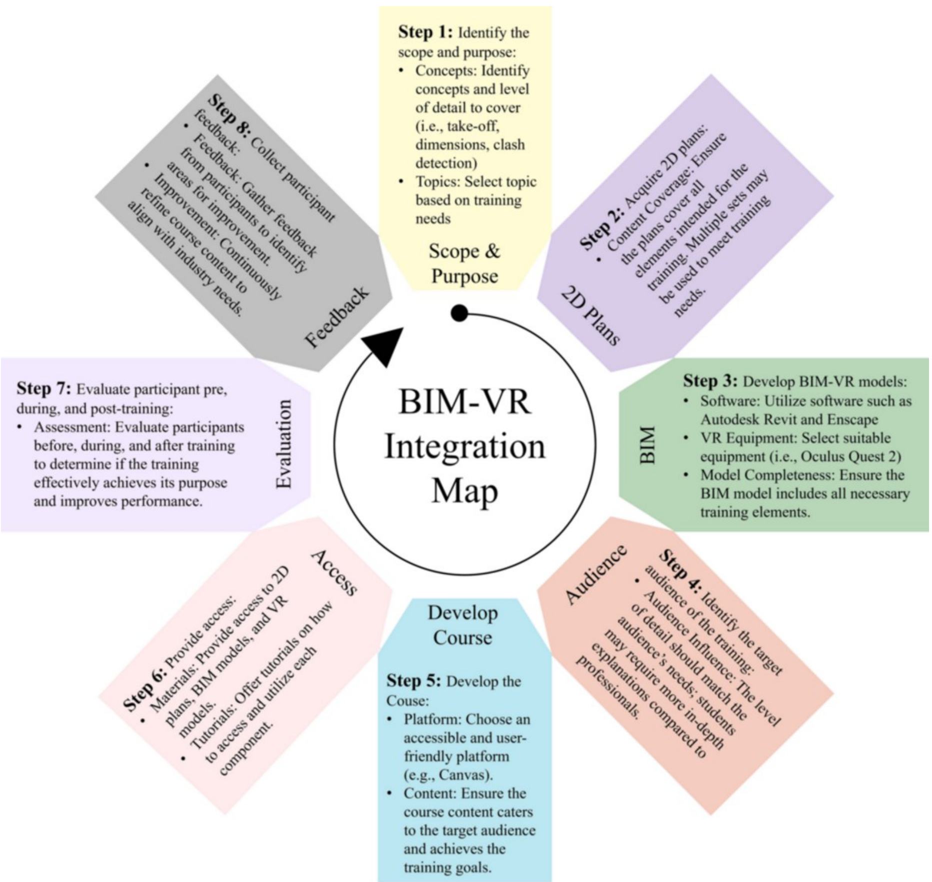

FIGURE 15: BIM-VR integration map

BIM-VR, Building Information Modeling-Virtual Reality

Conclusions

The presented work explored the BIM-VR application in an AECO classroom and investigated its effectiveness in enhancing MEP plan reading. BIM-VR potential within the context of MEP systems education has been minimally researched. A comprehensive literature review was completed to gain insight into the current status of BIM-VR utilization in the AECO industry, AECO education, and, more specifically, within MEP systems. The literature revealed that most studies relied on a qualitative assessment of BIM-VR, looking into participants' attitudes and opinions toward the proposed technologies. Therefore, this study bridges the gap in research where there is limited quantitative data on BIM-VR implementation in MEP system plan reading in AECO education.

Based on the literature, an appropriate commercial project was selected. In this study, BIM-3D and VR models were developed to improve the comprehension of MEP plan reading. The model was designed with the intent of allowing participants to interact with the integrated data in the model to complete tasks such as quality take-off, element identification, dimension measurement, and clash detection. Students from the CEM program were chosen as participants based on their limited experience with BIM, VR, and plan reading to minimize any interference from prior experience. The students were randomly divided into control and test groups. The effectiveness of the proposed approach was evaluated using pre- and post-quizzes and a questionnaire. The quizzes consisted of general questions, clash detection questions, and questions assessing the perceived difficulty of the quiz. The general questions tested students' knowledge of quantity take-off, dimensions, and element identification, while clash detection questions assessed their ability to identify spatial conflicts. Both groups received identical quizzes during both phases and were given the same amount of time to complete them. The control group had access to 2D plans throughout the study, whereas the test group had access to 2D plans in the pre-phase and BIM-VR models in the post-phase. After completing the post-phase, the control group also gained access to the BIM-VR models. Finally, both groups were asked to complete a questionnaire to evaluate their attitude toward the BIM-VR application for enhancing comprehension of MEP plan reading. The entire study lasted for 2 weeks to minimize the influence of a learning curve on the results.

Several statistical methods were employed to investigate the hypothesis that BIM-VR can enhance students' learning ability and better comprehend MEP plan reading. When all results and data presented were evaluated, the study concluded that the BIM-VR application to enhance MEP plan reading as a learning tool within the AECO classroom was effective. The test group outperformed the control group when BIM-VR was provided in the post-phase. Also, both groups expressed increased motivation and positive attitudes toward the proposed approach. Therefore, the study added to the literature by providing quantitative evidence of improved learning abilities when BIM-VR is incorporated into the learning environment. Consequently, it enables future applications to prepare students for future careers in the AECO industry with training on proposed technologies.

Also, the study provided a detailed setup, allowing replication of the proposed approach, hence aiding in further promoting the adoption of BIM-VR in academia as literature expressed the need for academia to catch up to industry. This was also achieved by highlighting BIM-VR's benefits on student learning experience both in performance and learning experience. As BIM-VR adoption in education grows, students and young professionals will be better prepared for industry demands.

While the pilot study aimed to serve as an initial check and made efforts to develop a combined quantitative and qualitative assessment as a preliminary analysis of BIM-VR effectiveness within the context of MEP education, the study presents some limitations:

• The proposed pilot study had a limited sample size of 21 students, which was constrained to the number of students registered. However, the limitation was addressed using a robust non-parametric statistical test designed to handle such data. Due to the limited sample size, there was no analysis of the influences of demographic differences such as gender, age, or student performance levels.

•The study was in a specific discipline, program, and university. Therefore, in future studies, there is a need to expand the investigation to other groups to obtain more generalizable data and provide a larger dataset to improve the robustness of the statistical analysis further.

• With the intention to limit the effect of a learning curve, the pilot study was limited to a timeframe of 2 weeks. The choice was intended to minimize prior knowledge bias on the results. In future studies, a more comprehensive exploration of BIM-VR implementation for teaching MEP plan reading could be extended to analyze insights into knowledge retention and long-term impact.

• The presented pilot study focused solely on BIM-VR adoption; future studies will aim to explore different extended reality technologies, such as AR, within the classroom and their potential to improve students' learning abilities.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Ri Na, Dyala Aljagoub

Critical review of the manuscript for important intellectual content: Ri Na

Supervision: Ri Na

Acquisition, analysis, or interpretation of data: Dyala Aljagoub

Drafting of the manuscript: Dyala Aljagoub

Disclosures

Human subjects: Consent was obtained or waived by all participants in this study. University of Delaware IRB issued approval 2242656-1. DATE: October 7, 2024 TO: Ri Na FROM: University of Delaware IRB STUDY TITLE: [2242656-1] Quantitative Analysis of BIM and VR Effectiveness in Enhancing MEP Plan Comprehension in AEC Education SUBMISSION TYPE: New Project ACTION: DETERMINATION OF EXEMPT STATUS EFFECTIVE DATE: October 7, 2024 REVIEW CATEGORY: Exemption category # 4(iii) Thank you for your New Project submission to the University of Delaware Institutional Review Board (UD IRB). According to the pertinent regulations, the UD IRB has determined this project is EXEMPT from most federal policy requirements for the protection of human subjects. The privacy of subjects and the confidentiality of participants must be safeguarded as prescribed in the reviewed protocol form. This exempt determination is valid for the research study as described by the documents in this submission. Proposed revisions to previously approved procedures and documents that may affect this exempt determination must be reviewed and approved by this office prior to initiation. The UD amendment form must be used to request the review of changes that may substantially change the study design or data collected. Unanticipated problems and serious adverse events involving risk to participants must be reported to this office in a timely fashion according with the UD requirements for reportable events. A copy of this correspondence will be kept on file by our office. If you have any questions, please contact the UD IRB Office at (302) 831-2137 or via email at hsrb-research@udel.edu. Please include the study title and reference number in all correspondence with this office. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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