EPiC Series in Built Environment
Volume 4, 2023, Pages 399–407
Proceedings of 59th Annual Associated Schools of Construction International Conference

Evaluating the Effectiveness of Building Information Modeling (BIM) and Virtual Reality (VR) in Understanding Mechanical, Electrical, and Plumbing (MEP) Plans

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The application of Building Information Modeling (BIM) and Virtual Reality (VR) has been explored within the context of the Architectural Engineering and Construction (AEC) industry to enhance visualization and communication among stakeholders. VR applications have extended into the AEC educational environment as a learning tool to aid students in better visualizing and understanding the project. This was done to mitigate the shortcomings of traditional 2D plans that are not as readily understood. The existing literature indicates that teaching Mechanical, Electrical, and Plumbing (MEP) plan reading with BIM/VR support has been explored minimally and qualitatively. The authors of this paper aim to fill this gap and present a quantitative study of BIM/VR applications in assisting MEP plan reading. In this study, the participants who are sophomore level students with minimal experience with BIM/VR and MEP systems were split into control and test groups, respectively. The effectiveness of learning was assessed statistically through pre-training and post-training quizzes. Furthermore, both groups were asked to complete a Likert scale questionnaire to evaluate their attitudes toward BIM/VR applications at the end of the study. The results show that BIM/VR integration significantly improved the performance of students.

Key Words: Mechanical, Electrical, and Plumbing; Building Information Modeling; Virtual Reality; Plan Reading.

Introduction

Plan reading is a critical skill and component of the Architecture, Engineering, and Construction (AEC) industry, as this is how essential information, details, and project scope are communicated amongst all parties involved in a project. Despite plan reading being a critical skill, many young AEC professionals fall behind in plan reading interpretation (Ghanem, 2022; Lee & Hollar, 2013). This is due to traditional 2D plans being limited in the extent of information they can provide. More specifically, they are disadvantaged in the visualization aspect and provide fragmented elements of the project such as views, sections, and elevations. Therefore, there is often misinterpretation of information and in many cases, this leads to financial and time losses (J. Wang et al., 2014). Mechanical, Electrical, and Plumbing systems are not excluded from those limitations, and in some cases are severely impacted due to their overly complex and intricate nature (Dallasega et al., 2021; Khanzode et al., 2008).

As a solution to the shortcomings of standard 2D plans, the integration of Building Information Modeling (BIM) along with Extended Reality (XR) applications has exponentially grown over the years (Ghanem, 2022; Gu & London, 2010; Mohamudally, 2018). Yet, this growth did not fully encompass the MEP systems, despite the fact that they can account for about 40% - 60% of the project cost and labor (Dallasega et al., 2021; Khanzode et al., 2008). The benefits of incorporating BIM/VR into a construction project can be extended into the MEP systems portion of the project as well. Therefore, the advantages of BIM/VR applications within MEP systems need to be evaluated and further explored.

BIM-VR Application in the AEC Education Environment

The combination of BIM/VR within the curriculum of AEC classes has been investigated, and the benefits were studied by a few researchers (Na et al., 2022). Amongst those who investigated it, most depended on student feedback through interviews and surveys (Alizadehsalehi et al., 2021; Wong et al., 2020). However, very few attempted to quantify the benefits of BIM/VR within the education context. Many researchers suggested a comprehensive framework of how the integration of BIM/VR can be adopted into the classroom (Ghanem, 2022; C. Wang et al., 2018).

A case study was developed in an attempt to assess the applicability and effectiveness of BIM/VR incorporation into the classroom (Alizadehsalehi et al., 2021). The authors developed a course that targeted the application of BIM/VR with 23 students as the participants. The students deemed motivation as the highlight of their experience, indicating that BIM/VR increased their enthusiasm to learn. Visualization, creativity, and interaction followed as the highlight of the experience (Alizadehsalehi et al., 2021). Another study introduced a framework for BIM/VR applications' integration in the classroom (Wong et al., 2020). Then, at the end of the study, a questionnaire was administered to evaluate the opinions toward BIM/VR incorporation into the classroom with a total of 57 participants. The analysis of the responses yielded that the students had positive attitudes toward the new learning experience with increasing enthusiasm to learn (Wong et al., 2020).

BIM-VR Application in MEP Systems

The incorporation of BIM/VR applications in both the AEC industry and education environment was focused on the architectural and structural elements of a project. However, there are limited applications of BIM/VR incorporation within the context of MEP. Among the limited number of related works of literature, most adopted a qualitative approach of surveys and questionnaires (Khanzode et al., 2008). The benefits of BIM/VR to aid in the interpretation of MEP systems are an extension of the general benefits provided by BIM/VR applications in the AEC industry and education environment. Some examples of said benefits include the reduction of RFIs, MEP coordination, and change orders. This produces more accurate as-built models allowing for easier facility management, significant reductions in cost and time, and fewer conflicts amongst all parties. This is due to efficient communication and collaboration of information (Khanzode et al., 2008).

In a case study attempting to evaluate the effectiveness of BIM/AR within the context of MEP systems, industry professionals were interviewed to evaluate the potential applications and benefits (Dallasega et al., 2021). Significant time reductions for the completion of several tasks were reported compared to the traditional methods. Also, measurement accuracy increased, especially for areas with high-complexity (Dallasega et al., 2021). Another case study quantitatively investigated the aspect of design in MEP systems, and the application of BIM/VR by statistically analyzing the pre and post-test scores of a control and test group (Espinoza et al., 2021). The study proved that BIM/VR enhanced the learning experience and increased the students' understanding of MEP systems. However, this case study did not extend to the aspects of building construction, such as interpreting MEP drawings, generating quantity take-off, performing clash detection, etc.

Problem Statement

MEP systems are complex and major components of construction projects. Due to these intricate systems existing within limited spaces, they are usually faced with many errors, clashes, and inaccurate estimates. This negatively impacts the construction process as it increases the time cost required to complete a project. Therefore, the application of BIM/VR can aid in interpreting and visualizing MEP components and systems. Yet, there is limited research exploring the full effect of BIM/VR combined application within MEP systems and its ability to enhance MEP plan reading skills. This case study aims to quantitatively evaluate the effectiveness of BIM/VR applications within the scope of MEP systems to test if it will increase the efficiency and accuracy of MEP plan reading. The study also aims to provide a method of enabling young AEC professionals to enhance their understanding of MEP systems with little experience in construction processes. Therefore, covering the gap where MEP systems have been minimally explored where both BIM/VR were applied simultaneously. Thus, a quantitative dataset provides insightful information within the AEC industry and education environment.

Research Approach

The study followed a general workflow as detailed in Figure 1, which consisted of conducting a literature review on the topic to systematically summarize the state of current research within the field. Then, a set of plans for a commercial building was selected for the purpose of the study. The plans were converted to a 3D/VR model. Next, the participants of the study were identified. The evaluation method of the effectiveness of BIM-VR assisting in MEP systems plan reading was developed. Finally, the results of the study were statistically analyzed, and its findings were reported.

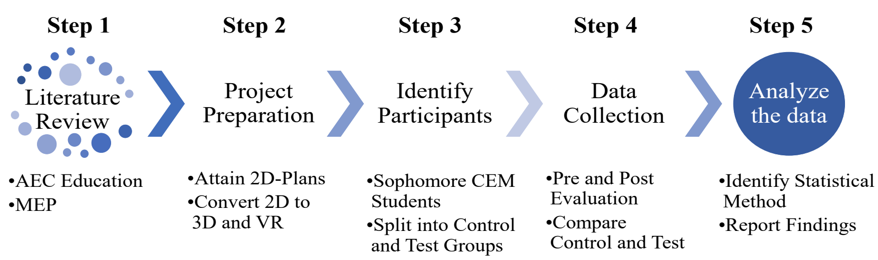


Figure 1. General workflow

Step 1: Literature review. The study's literature review focused on the application of BIM/VR within the scope of the AEC classroom. Next, BIM/VR applications within MEP systems in literature were highlighted. In each category, the research, approach, results whether results were qualitative or quantitative, and findings were studied and reported.

Step 2: Project Preparation. Next, the 2D plans of a retail facility (Goodwill Industries) were chosen as the base of evaluation. The plans were then converted into a detailed 3D model using Autodesk Revit 2022. The MEP components of the model were developed to match those in the plans as accurately as possible in specification, sizes, and dimensions. Then, using the Enscape plugin in Autodesk Revit, the model was exported to a VR-friendly platform. Next, using the Oculus Quest 2 VR goggles, the 3D model was VR accessible. Figure 2 illustrates the process taken, along with the software and equipment used to create the BIM/VR model.

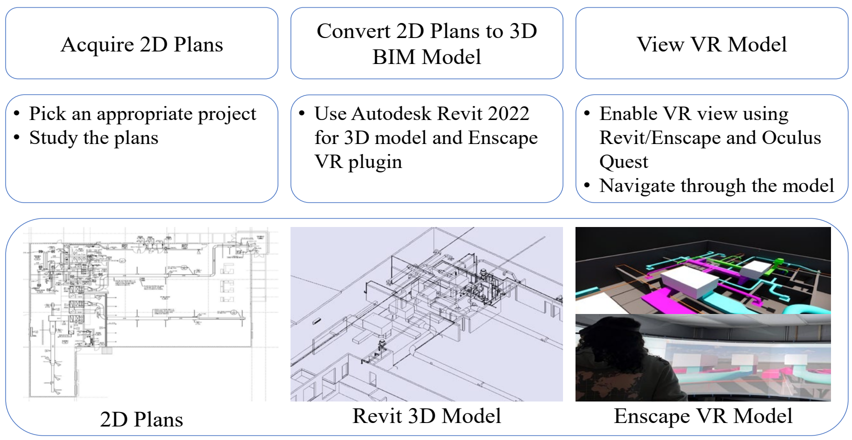


Figure 2. 2D to 3D/VR model process

Step 3: Identify Participants. The participants of the study were identified as sophomores of an entry-level CAD course within the CEM curriculum at the University of Delaware. The evaluation was conducted at the beginning of the semester, ensuring that all students have little experience with BIM/VR and MEP systems. The students were sectioned into a control group (11 students) and a test group (10 students) to fully evaluate the effectiveness of BIM/VR applications within MEP systems. The control group was asked to complete the tasks of MEP systems plan reading using only the 2D plans while the test group had access to both the 3D and VR models during the evaluation process.

Step 4: Data Collection. The evaluation process was completed over the course of two weeks. This ensured the elimination of a possible learning curve that can affect the results of the study. The evaluation consisted of a pre-quiz and a post-quiz in both the control and test groups (Figure 3). The questions for both groups were identical in both quizzes and covered general topics such as element identification, dimension, quantity take-off, and clash detection. The clash detection question asked students to identify components of the project where there was a clear violation of space constraints, in which two elements occupied the same space. The same parameters for clash detection were applied in both pre-and-post-quiz phases. The major difference is that the test group had access to the BIM/VR models during the post-quiz phase while the control group had access after the completion of both quizzes. Also, the control group was given a set of 2D plans that were generated from the 3D Revit model for the clash detection portion. This was to ensure that both groups had matching locations of clashes to allow for the evaluation of clash detection using 2D plans vs 3D/VR. Both quizzes consisted of a total of seven questions as further elaborated in Figure 3, and students were given 45 minutes to complete them. The pre-quiz was administered under identical conditions for both groups with access to only the 2D plans. The aim of the pre-quiz was to evaluate both the control and test group under identical conditions of no BIM or VR access. Then, both groups had a training session on MEP plan reading with the added topic of BIM/VR for the test group before taking the post-quiz. During the post-quiz, the control group had access to only the 2D plans while the test group was granted access to the 3D and VR models. This is aimed at evaluating the difference in the performance of both groups to identify if BIM/VR had a significant positive impact on learning how to interpret and understand MEP systems. After completion of the post-quiz, the control group was given access to both the 3D and VR models, then both groups were asked to complete a Likert-scale questionnaire on their perceptions of BIM/VR application for MEP plan reading. The entire process of quizzes and questionnaire were administered online through the university's platform as a multiple-choice quiz. The quizzes were completed during the class time while the questionnaire was completed at the end of the training outside of class time.

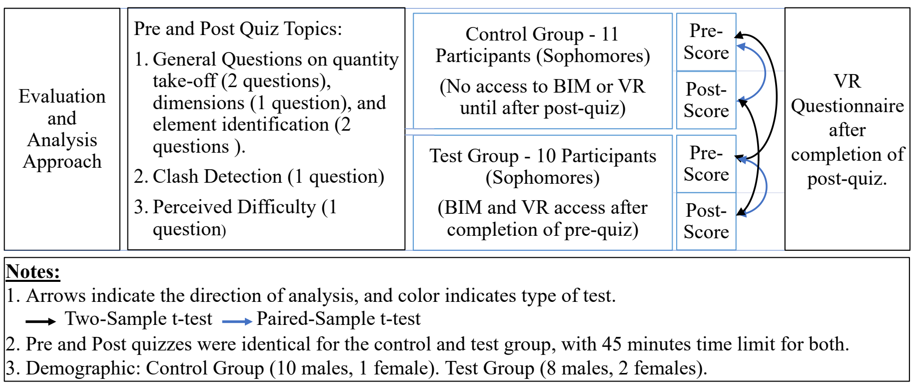
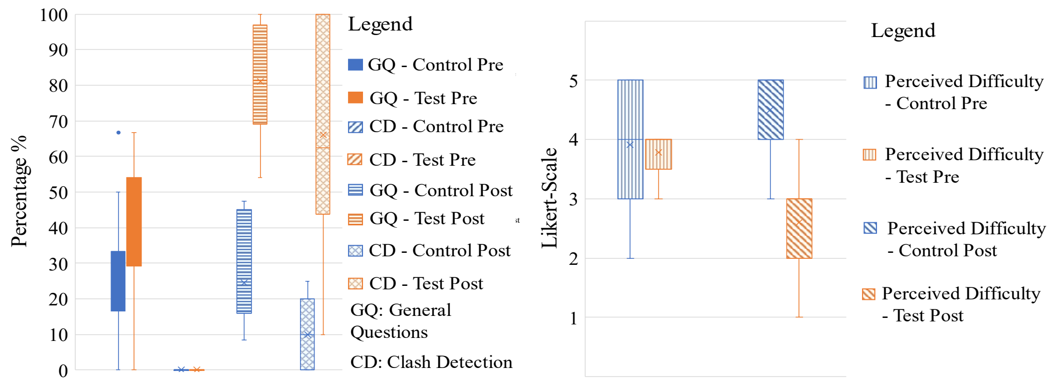


Figure 3. Evaluation and analysis approach

Step 5: Analyze the Data. Finally, the results of the experiment were analyzed using several statistical methods of a two-sample t-test, paired-sample t-test, and correlation coefficients. Figure 3 illustrates a graphical simplification of the evaluation and analysis approach. First, the pre-scores were analyzed across the control and test group on the general questions, clash detection, and perceived difficulty of the questions on the quiz to evaluate if any significant changes occurred. This was repeated for the post-scores results. Then, each group's results were analyzed separately from pre-to-post-scores. This was to study the impact BIM/VR applications had on the learning experience of MEP systems. Finally, the results of the questionnaire were evaluated to gauge the students' interest and attitude toward VR application for MEP system interpretation.

Results and Discussion

The results were clustered into three main categories: the analysis of the pre-to-post scores of the general questions, clash detection abilities, and perceived difficulty of the quiz questions. This was done across the control and test groups. Then, analysis was done for both the control and test group separately to further explore the significance of BIM-VR integration into the education environment of AEC. The statistical results are highlighted in Figure 4. A scale of 0 to 100 was utilized for general questions and clash detection portions and a scale of 1 to 5 for perceived difficulty. A score of 0 indicates significantly low performance for the quiz and clash detection portion, while a score of 1 implies that the students found the process to be extremely easy under the perceived difficulty category. On the other hand, a score of 100 would indicate a perfect score for the first two categories and a score of 5 indicates an extremely difficult process under the perceived difficulty portion.



(a) General Questions and Clash Detection (b) Perceived Difficulty

Figure 4. Statistical results

The control and test groups were tested comparatively to each other validating the importance of BIM/VR application in the classroom (Table 1 and Figure 4). First, the general questions portion, clash detection, and perceived difficulty scores were compared for the pre-phase. The t-test p-values were not significant for all, thus indicating that both groups performed similarly when both groups had no BIM/VR access. Next, when comparing the post results of the same categories, we see a significant increase in the test group's scores compared to the control group. Therefore, supporting the hypothesis that BIM/VR integration in the AEC classroom has a substantial positive impact on improving the students' interpretation of MEP plans and concepts such as clash detection, quantity take-off, dimensioning, etc. The correlation coefficient was also produced from the post-phase comparing the control and test groups as shown in Figure 5. A 0 on the x-axis means students had no access to BIM/VR (control group) and 1 indicates access to BIM/VR (test group). Also, correlation coefficients range from 0 to 1, with 0 being no correlation, and 1 indicating a strong correlation. Hence, there is a substantial correlation between score improvement for both the general questions and clash detection portions with values of 0.8907 and 0.7705 when BIM was used. As for perceived difficulty, there is a strong negative correlation (-0.7889), indicating that the test group utilizing BIM/VR viewed the quiz to be much easier than the control group that did not have BIM/VR access.

Table 1

Paired and two sample t-test and results

Item	P-value (Prob > t)	P-value (Prob > t)	P-value (Prob > |t|)
	Quiz Score	**Clash Detection**	**Perceived Difficulty**
Test vs Control Group (Pre to Pre)	0.0871	-	0.6877
Test vs Control Group (Post to Post)	<0.0001*	0.0002*	<0.0001*
Control Group (Pre to Post)	0.6254	0.0034*	0.0248*
Test Group (Pre to Post)	0.0002*	<0.0001*	0.0023*

*Significant

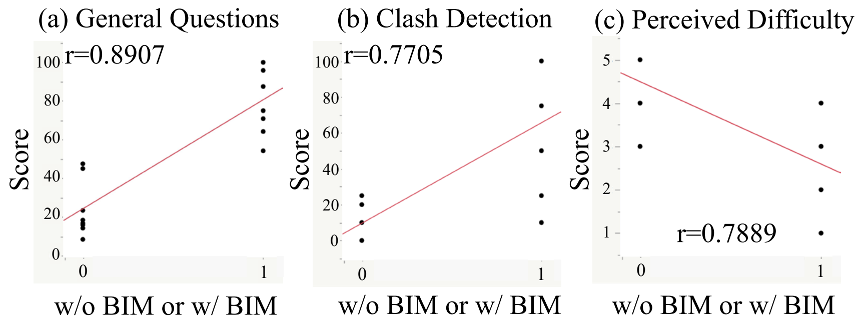


Figure 5. Correlation coefficients (control vs test post-phase)

Moving on, when inspecting the t-test p-values for the control group as shown in Table 1, they showed no significant change in scores for the general questions portion from pre-phase to post-phase. This is also illustrated in Figure 4. The score in pre-phase and post-phase is 27.3% and 24.5% respectively, which are very close to each other. However, the score seemed to show some increase in the clash detection portion after the orientation. This was due to students' lack of knowledge of what clash detection represented before participating in the training session. Therefore, students were unable to answer that portion correctly in the pre-quiz phase. This explains the 10% score increase in clash detection ability for the control group as they were able to at least try and identify possible clashes using the provided 2D plan set generated from the 3D Revit model. Yet, this is still well below the acceptable level of clash detection comprehension and identification. Also, the perceived difficulty has significantly increased from 78% to 90% despite the previously mentioned training session aimed at familiarizing the students with MEP plans (Figure 4). It can be concluded that the control group's performance in MEP system interpretation was not improved within the short training period when the only access to 2D plans of MEP systems was provided. Furthermore, there is a trend of a considerable amount of variability in scores for both the pre and post-general questions portion (Figure 4). As for the case of the post scores of clash detection, it appears that the scores were centered towards the lower end of the plot with some variability (Figure 4).

Next, the same steps of analysis followed for the control group were applied to the test group (Table 1 and Figure 4). The mean of scores significantly increased from 40% to 81% for pre-vs-post-scores for the general questions portion. A significant improvement in clash detection was observed where the scores increased from an average of 0% in the pre-quiz phase to a 66% in the post-quiz phase. Finally, the perceived difficulty associated with completing the quiz significantly decreased from 75.6% to 52.0%. Those results indicate that when students were given access to BIM/VR to aid in the interpretation of MEP plans, their performance significantly improved compared to when they did not have access to said resources. Also, the variability in the scores for the test group decreased in the post-phase of the general questions portion compared to the pre-phase. As for clash detection, the test group's clash detection post-scores were considerably variable. This can indicate that the comprehension of the concept of clash detection improved for some students while others still needed more training or more time to familiarize themselves with the mechanism of identifying clashing elements.

Finally, the results of the Likert-scale questionnaire were evaluated as presented in Figure 6. The questionnaire included questions investigating students' familiarity with VR applications, and the various ways it helped them with the application of MEP systems. The questions included topics such as enhanced motivation, visualization, comprehension, clash detection ease, and status of the learning experience. Both the control and test groups were asked to complete the questionnaire, and according to the results, the students had positive feedback on their experience with using BIM/VR to interpret and read MEP plans. The average response was almost above 4 for all questions, except the previous experience with VR which scored below 3. The students seemed to value the visualization and clash detection aspects of BIM/VR the most, as they had the highest average approval response of 4.8 and 4.7, respectively compared to the total average of 4.4 out of 5.0.

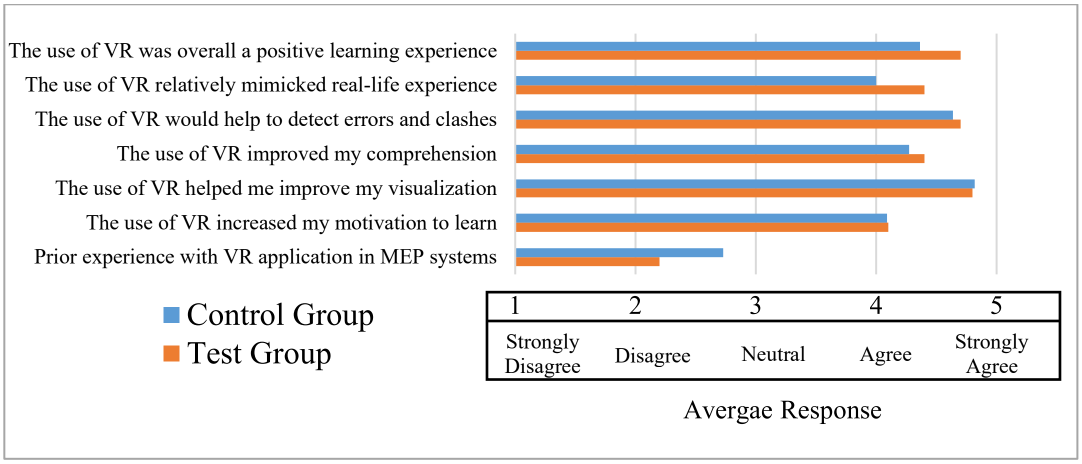


Figure 6. Questionnaire results

Conclusion

The results confirmed that the integration of BIM/VR is significantly beneficial to students' performance when interpreting MEP plans. First, the score average was considerably higher when comparing the control group to the test group in the post-quiz phase. Next, there was a significant increase in the test group's performance when comparing the pre-to-post scores. Furthermore, there is a similar trend when it comes to analyzing the students' ability to complete clash detection tasks where the test group performed much better compared to the control group during the post-phase, and there was a significant increase in their post-scores compared to the pre-scores. As for the perceived difficulty portion, there is an increase for the control group from the pre-to-post phase, where they seem to have not felt an improvement in their ability to answer the question with only 2D plans. Yet, there is a significant decrease in perceived difficulty for the test group from when they only had access to the 2D plan (pre-quiz) to when they had access to both BIM/VR (post-quiz). Furthermore, according to the questionnaire results, the students had very positive attitudes toward the application of BIM/VR. Therefore, this study concludes that the incorporation of BIM/VR into the AEC classroom enhanced the interpretation of MEP plans and systems. The study was conducted on an accelerated schedule of two weeks. The absence of a learning curve on the ability to better read 2D plans, it was proved that BIM/VR applications in education can scientifically improve and accelerate comprehension of MEP systems. In future studies, this experiment can be conducted in a MEP class over the duration of a semester. This would allow the students more extensive training on 2D plan reading for MEP systems, thus further evaluating the benefit of BIM/VR incorporation into the classroom.

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