Assessment of AEC Students’ Performance Using BIM-into-VR

Sepehr Alizadehsalehi *, Ahmad Hadavi and Joseph Chuenhuei Huang

Abstract: Building Information Modeling (BIM) and Virtual reality (VR) have attracted growing attention within the architecture, engineering, and construction (AEC) industry in recent years. Integration of BIM and VR technology can develop workflow efficiency through enhanced common understanding and prepare students in architecture and engineering programs to become leaders of the AEC industry. However, the current shortage of AEC professionals trained in BIM and VR is still a barrier to collaborative working practice in this industry. This paper reviews previous work on the BIM, VR, and BIM-into-VR in AEC education/training to bridge this gap. It also presents an advanced framework to clarify creating and using the BIM model into VR workflow in the AEC industry through the integrated definition function (IDEF0) model. The authors further evaluated the BIM-into-VR applications in literature and real-life by surveying students’ learning performance in terms of eight characteristics relevant to the VR environment and students’ performance within two projects, one involving the “NASA Mars Habitat Project” and the other involving the “Norris Center Project” at Northwestern University. The results confirmed that BIM-into-VR usability and efficiency in improving students’ main learning performance characteristics: Learnability, Interoperability, Visualization, Real-world, Interaction, Creativity, Motivation, and Comfort. This study addresses the advantages of using BIM-into-VR in AEC programs. It also offers suggestions to AEC educators and students in implementing BIM-into-VR in different courses and creating a roadmap for their future as professionals in the AEC industry.

Keywords: virtual reality; building information modeling; performance assessment; AEC education

1. Introduction

Recent technological advances in visualization and analytics have helped academic and industrial researchers take tangible steps toward improving design and construction projects’ quality and efficiency and succeed on projects’ cost and schedule. Building information modeling (BIM) as a database of information that created a multi-dimensional (n-D) knowledge resource and model are swiftly becoming the standard process for communicating all stages of Architectural, Engineering, and Construction (AEC) details [1]. BIM is a powerful tool for: design a high-quality 3D model; analyze various design options; detect clashes among different elements; perform energy simulation; plan and schedule; achieve quantity takeoff, estimate cost, and generation of procurement plans; coordinate a model among various project stakeholders and improve communication among project stakeholders; visualize the as-built model; enhance the quality of inspection; and facility management [2–7]. BIM encourages all stakeholders to participate in and collaborate to achieve a high-quality product in all project phases. Thus, specifying, articulating, and presenting a significant precision and transparency level in BIM models’ consistency and content is essential [8].

Recent new technologies in Virtual Reality (VR) headsets and software have led researchers to experiment and view n-D BIM content [8,9]. This innovation allows for immersive virtualization of a BIM model. As one of the most significant disruptive technologies, VR headsets have been tried for a range of challenges inherent in the AEC industry.
industry [10]. These challenges include decision-making during initial conceptual design and planning processes, design coordination, clash detection, facility management, project planning, urban design, and safety, design, and construction training. In the last decade, several companies had initiated VR development and its application that resulted in VR entering into a new period of full development [3,11–14]. Large construction projects are inherently complex, and therefore require well-prepared architects and engineers. To handle such complexity, AEC students are expected to have the proper training and be well equipped for the latest challenges. Over the last decade, BIM and VR technologies have manifested unlimited potential for both academic and industrial communities in many disciplines.

Developing BIM and VR applications can help in solving many educational and training problems [15]. However, having this virtual educational environment requires students to understand the process, devices, platforms, and software used in real projects. Thus, recent research papers on the concept of BIM and VR in the AEC industry and education/training environment were reviewed. This research offers a structure created to explain the methods of generating and using the BIM-into-VR model for design and construction projects through an integrated definition function (IDEF0) model language. This article also evaluates the effectiveness of BIM-into-VR technologies in literature and real life by surveying students in the MPM program at Northwestern University in terms of students’ learning performance (Learnability, Interoperability, Visualization, Real-world, Interaction, Creativity, Motivation, and Comfort). Figure 1 presents the stages included in this study: Step 1 presents an extensive state-of-the-art review of the main concepts of BIM, VR, and BIM-to-VR in the AEC industry and BIM-into-VR in AEC education. Step 2 presents the created IDEF0 model for using BIM-into-VR clearly and comprehensively in the AEC industry. Step 3 and Step 4 present the evaluation of using this integration in a two-pronged methodology by conducting a broad literature search and surveying students after experience in two different case studies. Step 5 presents a discussion of the study findings, its theoretical and practical contributions, and the present research limitations.

2. Theoretical Background

This segment summaries significant research projects in the four main areas related to topic of this research: (1) the evolution of BIM in AEC; (2) visualization of BIM model over VR (BIM-into-VR); (3) Development of an IDEF0 model for BIM-into-VR workflow; and (4) application of BIM and VR in AEC education/training.

2.1. The Evolution of BIM in AEC Industry

Saieg, et al. (2018) defines BIM as: “BIM is a set of interacting processes, roles, policies, and technologies creating virtual information-based models to manage data in the digital format used within the AEC industry to design, construct, and maintain a project throughout its life-cycle” [16]. BIM has been accepted as a valued tool for improvement in the design and construction stages of projects due to its rapid growth, adoption, and implementation. BIM has become the standard process for communicating design and construction details in AEC projects. Different vendors have produced many applications
with powerful BIM functionalities to create, implement, and manage nD BIM models, which can be used in the project’s lifecycle [17].

Domain professionals must iteratively update BIM data during a project due to the growing set of requirements and complex systems of a construction project [18]. This information needs to define and explain by a significant level of trust, precision, and transparency in BIM models. Different disciplines utilizing BIM in the construction environment have various nomenclatures, varied vocabularies, different data formats and geometries, diverse computing paradigms, and distinct essential world views [3]. These disciplines and construction companies have different standards and processes for their communication and delivery procedures. One way to solve these issues is the standardization of implementing BIM and utilization of a detailed BIM Execution Plan (BEP) [19]. The application of BIM in AEC projects for design, construction, and maintenance would generate, manage, and support critical data, information, and reports. The BIM application will lead to realizing a cost-effective design and better communication among AEC professionals. Table 1 shows some of the different applications for BIM, which have been defined from the literature.

Table 1. A selection of the most widespread Building information modeling (BIM) advantages based on academic publications.

| No | Application Area                                                                 | References |
|----|----------------------------------------------------------------------------------|------------|
| 1  | Analyze, review, and evaluate the impact of various design options                | [20–22]    |
| 2  | Spend more time on design instead of contract documentation                        | [23,24]    |
| 4  | Enable documentation automation (better accuracy)                                 | [25,26]    |
| 5  | Enable quicker reviews for permits and approvals                                  | [19,27]    |
| 6  | Coordinate Design                                                                 |            |
| 7  | Encourage energy conservation for sustainable building systems                     | [31,32]    |
| 8  | Plan risk scenario                                                                | [33,34]    |
| 9  | 4D model of construction process                                                  | [35–37]    |
| 10 | Quantity takeoff and cost planning with 5D simulation                              | [38–40]    |
| 11 | Coordinate and Clash detection                                                    | [28,41]    |
| 12 | Reduce in RFI’s, change orders, claims, and conflicts                             | [42,43]    |
| 13 | Reduce in construction and production costs                                       | [44,45]    |
| 14 | Reduction in project delivery duration                                            | [19,45]    |
| 15 | Facilitate modular construction                                                   | [46,47]    |
| 16 | Increase prefabrication                                                           | [48–50]    |
| 17 | Reduce in site materials waste                                                    | [51–53]    |
| 18 | Improve construction safety                                                       | [54,55]    |
| 20 | Increase client engagement                                                        | [31,56]    |
| 21 | Increase productivity, efficiency, and quality of project                         | [57,58]    |
| 24 | Encourage use of other technologies (Sensors/VR/AR/MR/GIS/etc.)                   | [15,19]    |
| 26 | Improve collaboration and communication between disciplines                        | [15,59]    |
| 27 | Allow for long-term data assessment                                                | [19,60]    |

Note: 5D = five dimensional; VR = virtual reality; AR = augmented reality; MR = mixed reality; GIS = geographic information system.

BIM is an essential piece of the solution, helping to deliver more efficient design, build, and operations, but its value grows exponentially when shown in a more realistic way than a 3D model. To understand the VR concept, it needs to be broken into two characterizations of psychological and technical. Perception and simulation are the two main keys to VR. Humans’ perception of reality is a blend of sensory information and how humans manage this information to shape their awareness of what is going on, how it is going on, where it is going on, when it is, and why it is going on. VR shows these schemes and processes with information that is not really there but is captivating enough for us to feel it as reality. VR is an emulation of a situation that humans see or feel as real. VR defines a digital setting that can be experienced and explored by a person from a technical perspective. Four significant conditions must be achieved in order for a VR
experience to be considered a success. It must be believable, interactive, explorable, and immersive. VR is a simulation and immersive environment projected through a wearable headset that places the curated world in the user’s sight. The main incentive for using a VR application is that it provides the possibility to test with those circumstances that “cannot be accessed physically,” “expensive be accessed physically,” or “dangerous be accessed physically” [61]. With the continuous development of technology, VR technologies have attracted the increasing attention of a broad area of applications [62], such as architecture, cinema and entertainment, risks identification, medical science, video games, engineering, urban design, education and training, and so on.

Research on VR technology applications in various stages of AEC projects has shown the benefits these applications can bring to all projects [63]. VR technology has been effective in project schedule control [64] and construction safety training [65]. It can also identify design issues [61] to help users comprehend a project complexity, make better design decisions, and improve collaborative decision-making [3]. VR technology provides environments for greater collaboration among project participants [66] and enables a better understanding of complex designs [67]. There are some VR software applications developed by gaming engine (e.g., Unity, and Unreal) which allow the users to have the interactive simulated feelings. In addition, the applications like IrisVR and Resolve provide the multiusers meetings built for instant collaboration in the VR environment. All stakeholders can benefit from VR at various project design phases—namely, schematic design, detailed design, construction detailing, and maintenance [68]. Architects and designers can use VR technology from beginning design mock-ups to project collaboration to the end of the project. VR has the potential to sell an idea stronger and better than other applications. Jumping into VR during the concept and layout process allows the designer to justify a proof of concept. VR enables users to see and interact with the actual design. A virtual walkthrough experience is superior to the already-great experience of seeing the project in 3D or 4D on a large screen or a projector [69]. This enhanced experience enables all stakeholders to get a feeling for space and design that they are not able to get through other ways, not even with a BIM model. Architects can work through design errors in a virtual space, improving the chances of spotting problems before starting the project.

VR can provide an entirely new understanding and appreciation of design. This is because VR offers the ability to test in context [70]. Contractors can now bring the job site to the office and even walk a fully constructed rendering of their project before breaking ground. VR can be a highly efficient communication platform for stakeholders who are not from the AEC industry and have no cognizance of regular construction contracts. Further, VR reduces the understanding gap among project owners and designers and visual and non-visual thinkers. The ability of VR to grab the attention of people in a project presentation session that might otherwise be boring can be considered another benefit of using VR during project design development and construction. VR provides the ability for CAD data to be viewed from every direction and helps accelerate the design workflow. When it comes to clients, immersing them in the model enhances understanding the concept while validating the overall design. Clients can also experience a more natural interaction with designs, allowing for walk-throughs that feel more realistic, especially for non-CAD experts. VR also assists in resolving logistical concerns faster by employing in a shared, immersive environment. Safety issues, transportation routes, and site staging can be addressed earlier. During the design process, VR allows problems to be identified by viewing real scales’ issues. Finally, architectural engineering construction projects can utilize VR to view remote locations, reduce travel time, and optimize the overall expense. For the AEC and manufacturing industries, VR provides a new age of efficiency, connectivity, and mobility that offers new opportunities to advance their competitive advantages while becoming more productive and safe in their practices. Table 2 shows some of the different VR applications in the AEC industry, which have been defined from literature.
Table 2. A selection of the most widespread Virtual reality (VR) benefits based on academic publications.

| No | Application Area                  | References       |
|----|-----------------------------------|------------------|
| 1  | Simulation/visualization          | [71,72]          |
| 2  | Communication/ collaboration       | [73,74]          |
| 3  | Information access/evaluation      | [3,13]           |
| 4  | Risk assessment                   | [34,75]          |
| 5  | Progress monitoring               | [76,77]          |
| 6  | Education/training                | [61,78]          |
| 7  | Safety management                 | [77,79]          |
| 8  | Client satisfaction               | [63,77]          |
| 9  | Review design options             | [74,80]          |

2.2. Visualization of BIM Model over VR (BIM-into-VR)

The process of BIM usage signifies an advancement compared to customary procedures of developing and managing construction projects. Even though BIM adaptation has grown in recent years, there are still obstacles and restrictions in its comprehensive implementation [81]. Using VR to visualize the rich, accurate, and smart data included in a BIM model can support and produce interactive real-time project visualization for a consistently shared perception with main participants [3,82]. This arrangement has also shown a prospect of allowing the project leadership to envision and identify a project’s intricacy for successful communication in all stages. Table 3 summarizes the published study works which employed VR with or without BIM for AEC projects.

Table 3. Using VR alongside BIM in diverse areas of design and construction industry.

| Number | References | VR | Included BIM | Purposes                                   | Phase | Evaluation Approaches |
|--------|------------|----|--------------|--------------------------------------------|-------|-----------------------|
| 1      | [3]        | √  | √            | Construction project management            | √     | √                     | Case study |
| 2      | [61]       | √  | √            | Design and construction education          | √     | √                     | Survey     |
| 3      | [65]       | √  | √            | Construction safety                        | √     | √                     | Review     |
| 4      | [82]       | √  | √            | Collaborative decision making              | √     | √                     | Case Study |
| 5      | [83]       | √  | √            | Construction safety training               | √     |                       | Case Study |
| 6      | [84]       | √  | √            | Review and comparison of VR and AR         | √     |                       | Survey     |
| 7      | [85]       | √  | √            | Collaborative decision making              | √     | √                     | Case Study |
| 8      | [86]       | √  | √            | Construction safety                        | √     | √                     | Case Study |
| 9      | [87]       | √  | √            | Construction safety                        | √     | √                     | Case Study |
| 10     | [88]       | √  | √            | Goals, challenges, and benefits of VR in AEC industry | √ | Interviewees-Case Study |
| 11     | [89]       | √  | √            | Construction safety training/jobsite management. | √ | √ | Case Study |
| 12     | [90]       | √  | √            | Building energy performance gap            | √     | √                     | Case study |

Note: VR = virtual reality; AR = augmented reality; AEC = architecture, engineering, and construction; BIM= building information modeling; D = design; C = construction.
Nowadays, in most design and construction firms, BIM is somewhat a standard for AEC projects, but most of these firms do not use VR systems. Like BIM, which works with BEP, the VR needs to work based on a comprehensive workflow. A common VR development workflow is prepared after a project owner is requested to use VR technology and approves it. Then, the VR group will be brought to the project. The VR conversion would be performed by using a commercial software product or in-house. VR requires headsets and sensors to track location and movement and stereo headphones to produce surround sound. Figure 2 summarizes all the available processes and steps for converting a BIM to a VR model.

Figure 2. BIM-into-VR integration map: From BIM models into VR toolsets (2010–2021).

IDEF0 is an acronym for ICAM definition for function modeling, where ICAM stands for integrated computer aided manufacturing. IDEF0 is a methodology that can describe complex functions such as technological practices and that allows for the development, analysis, and integration of systems such as BIM and VR. The proposed model represents a safety management model for construction sites. The model is described schematically as an IDEF0 diagram. The authors describe the BIM-into-VR workflow in this model to help everyone understand the processes. The boxes in Figure 3 describe key processes. The model designed by the authors of this manuscript is based on their knowledge from previous publications, industry case studies, and their experiences as a best practice process. Figure 3, illustrates all stages of creating a 3D or 4D (3D + time) model (optional) up until the time that model is used in VR for different purposes in the AEC industry. All steps of generating models in the design phase until it is converted to use in VR in a construction project are presented in Figure 3. Step 1 is collecting data that comprises structural, architectural, and MEP designs in 2-D and 3-D models and essential data regarding schedule and cost (if 4D BIM is required). Incorporating this information generates a federated 4D-BIM/as-planned model (A31) and (A32). A VR model is created based on specifications, BIM knowledge, and designers’ and stakeholders’ ideas (A33). The generated VR model can be utilized to analyze the design and evaluate different design choices to perform remedial actions on design and make better design choices (A34). When the problems are fixed and stakeholders have accepted the design, it is then transferred to the construction
site managers to evaluate and understand the design and implement, analyze, and control the project (A35).

Figure 3. BIM-into-VR workflow based on IDEF0 Model.

2.3. BIM and VR in AEC Education/Training

Institutional education has a vital role in BIM transition. Future AEC community leaders who can transform the industry paradigm throughout their careers are universities’ products. Numerous researchers have stated the significance of BIM-based education in AEC-related programs. Sacks and Barak [91] replaced traditional civil engineering graphics courses with BIM for first-year students. Azhar et al. [92] examined the effectiveness of BIM instruction by surveying students’ perceptions. They demonstrated how BIM improved students’ understanding of construction project management. Research by Clevenger et al. [93] identified several methods in that BIM can be incorporated into the curriculum. These include providing standalone courses and/or updating existing courses to embed material on BIM. In another study, Wong et al. [94] studied the status, weaknesses, strengths, and professional possibilities of BIM-based education. Peterson et al. [95] added BIM to their construction project management courses and showed how BIM could support and increase student understanding. Khosrowshahi and Arayici [96] found teaching BIM is vital in the AEC industry roadmap for BIM execution. Abdirad and Dossick [97] propose that BIM is an essential subject to be taught in college because of industry demands and because the development of strategies for delivering BIM is complex. Shelbourn et al. [98] studied very similar research about integrating BIM into the USA and UK undergraduate curriculum. The investigation highlighted a discussion regarding whether BIM should be a standalone unit or integrated into courses. The study recommended that BIM present students with an opportunity to understand the building’s
construction methodology further. For instance, Zou et al. [99] observed the necessity to optimize BIM-based education resources to bridge the gap between academia and industry practice. Jin et al. [100] researched on students’ understanding of and individual views of BIM that were intuitive to both BIM instructors and companies.

On the other side, the number of VR scenarios can be broadly applicable to many education and training areas. Many researchers have remarked on the significance of VR-based education in programs related to AEC. VR can generate different virtual learning environments, tough to touch, dangerous to manage, or even things that do not exist in reality [101]. Pedro et al. [102] results indicated that their BIM-based VR system could experientially improve hazard identification ability, transfer safety knowledge, and engage students. VR allows learners to investigate virtual environments from different viewpoints, empowering them to freely examine creative impulses and provide them with a more comprehensive understanding of learning targets [103]. Therefore, VR technology is less risky and more cost-effective than conducting scenarios in reality. Bhagwat and et al. [104] believed that the advent of new visualization platforms such as building information modeling (BIM), virtual reality (VR), and gaming technologies provides a unique opportunity for the AEC students to see and experience the new ways of design, implement, and manage safety. In summary, VR technologies have the potential of:

- Providing outstanding visualizations that were not imaginable in a traditional system;
- Creating curiosity by helping students become more dedicated and inspired;
- Increasing student commitment by grabbing and holding their attention (because VR makes it challenging and thrilling to interact, create, and manipulate objects in a virtual setting);
- Helping students realize intricate topics, concepts, and theories;
- Improving the quality of instruction by introducing new practices and opportunities for learning by doing;
- Reducing barriers of language for international learners;
- Adding precision and permitting the visualization of things, elements, or processes which difficult to present in a real environment;
- Enabling students to interact collaboratively for the first time and, for those students already using VR, increasing their ability to interact and collaborate;
- Providing instructors’ instant feedback for students;
- Offering the ability to repeat practice in a safe setting.

From instructors’ perspective, to teach students for BIM-into-VR approaches, there is a need for necessary and sufficient conditions such as the available VR technologies and their potentials; how to apply them to our daily life and AEC industry; and the workflows from BIM-into-VR. With VR, we can review our design and construction with a human scale and simulate safety issues before exposing them to dangerous conditions. The challenge instructors have to think about while teaching all kinds of reality technologies is perhaps, some technical things those students learned this year might not be workable or applicable next year because of the rapid technological change. They need to encourage students to understand the concept and learn the methodology instead of the step-by-step procedures. In addition, students need to explore the latest VR applications and be prepared to apply that once they graduated and use them in real-world scenarios on the projects.

3. The Research Methodology and Approach

3.1. The Evaluation of BIM-into-VR in AEC Education

VR-powered BIM is a new development in the design and construction training environments that has already created instructional changes to tertiary education methods. In contrast to pure BIM, the BIM-into-VR helps students greater design visualization and contributes to a better understanding of the project data and objectives. If the BIM model is designed in a high enough level of detail (LOD), visualizing BIM via VR gives AEC students a more realistic sense of materials, project concerns, and decision-making processes. This visualization is entirely in line with Bloom’s taxonomy of the cognitive
domain and supports education, instruction, and assessment. VR-powered BIM can provide for all the learning steps: remembering, understanding, applying, analyzing, evaluating, and creating. Visualizing BIM via VR augments BIM functionality for AEC students by helping students understand how BIM can be used in every field operation. This section aims to comprehend the usefulness of the BIM-into-VR if employed in the AEC education environment and students’ performance characteristics, as shown in Figure 4. Learning is invisible until it is assessed through performance. Assessment design for students’ performance can be challenging, and the instructor should be cognizant about the students learning styles. Students must be evaluated for their learning based on factors that influence their performance. The required new form of teaching and its assessment is different from the traditional evaluations. Previous research has described some of the main characteristics that university professors consider in evaluating students’ learning performance. The VR/AR/MR course instructor, based on previous research and his teaching experience, has selected the following eight characteristics as the most relevant factors to assess performance.

![Figure 4. VR features related with student's performance.](image)

A two-pronged approach was used to assess the BIM-into-VR in the AEC education setting. (1) The use of BIM-into-VR in the AEC-related education setting was justified by reviewing previous studies that discussed these technologies. (2) This system was evaluated by twenty-three (23) students of the MPM program of the Department of Civil and Environmental Engineering at Northwestern University. In this evaluation, the students were asked about various factors that affect their education quality.
3.2. Previous Research

Due to this research’s investigative objective, the previously published study was reviewed on the role of VR in AEC education to justify BIM-into-VR use in such environments. Thirteen (13) published research papers were evaluated to collect suggestions that BIM-into-VR application in the education setting has many advantages. Applying BIM-into-VR to improve AEC students’ learning outcomes, especially in perceived learning effectiveness, is a novel area that shows students can operate the objects by simulating the real scenes in skill training and visualizing them into the virtual environment repeatedly. The BIM-into-VR framework is enhancing the learning experience and learning outcomes for construction education within AEC curricula. As shown in Table 4, a number of researchers have considered these eight characteristics to a different level of importance. Therefore, the instructor considered all different characteristics in his assessment that other researchers used.

**Table 4. Research on BIM-into-VR characteristics related to student’s learning performance.**

| Number | References | Learnability | Interoperability | Visualization | Real World | Interaction | Creativity | Motivation | Comfort |
|--------|------------|--------------|------------------|--------------|------------|-------------|------------|------------|---------|
| 1      | [61]       | *            | *                | *            | *          | *           | *          | *          | *       |
| 2      | [105]      | *            | *                | *            | *          | *           | *          | *          | *       |
| 3      | [106]      | *            | *                | *            | *          | *           | *          | *          | *       |
| 4      | [107]      | *            | *                | *            | *          | *           | *          | *          | *       |
| 5      | [102]      | *            | *                | *            | *          | *           | *          | *          | *       |
| 6      | [108]      | *            | *                | *            | *          | *           | *          | *          | *       |
| 7      | [109]      | *            | *                | *            | *          | *           | *          | *          | *       |
| 8      | [110]      | *            | *                | *            | *          | *           | *          | *          | *       |
| 9      | [111]      | *            | *                | *            | *          | *           | *          | *          | *       |
| 10     | [112]      | *            | *                | *            | *          | *           | *          | *          | *       |
| 11     | [113]      | *            | *                | *            | *          | *           | *          | *          | *       |
| 12     | [114]      | *            | *                | *            | *          | *           | *          | *          | *       |
| 13     | [9]         | *            | *                | *            | *          | *           | *          | *          | *       |

Frequency 13 5 10 13 9 10 7 2

Note: * = mentioned.

“Learnability” and “Real World” are the most significant advantages recognized in the majority of reviewed articles. As shown in Table 4, there is sufficient evidence that the use of BIM and VR in AEC education environments is desirable and beneficial. The suggested BIM-into-VR-based structure is expected to improve students’ learning performance, provide an environment similar to real-world, increase the visualization of models before they were built, and enhance their creativity.

3.3. Student Evaluation: Case Study

The Sample

The participants in this study were graduate students who registered in an elective course titled “Integrating VR/AR/MR with Design and Construction” in the Spring Quarter 2019. The course had 23 students from diverse experiences such as construction management, architecture, real estate, and sustainability. The goal was for students to learn the concepts and workflows related to BIM and different available VR devices, get hands-on experience with these devices, and understand how BIM models into VR devices are different from what they see on pure BIM models. This project also helped them understand how BIM and VR integration allow them to see, analyze, and understand project data, making more precise decisions in real projects in their careers.

The students’ evaluation of the BIM-into-VR environment consisted of five steps that are shown in Figure 5. Step 1 involved identifying and preparing course goals and curriculum by the MPM program and the course instructor. Step 2 involved creating two different evaluation models: (1) Norris Center Project and (2) NASA Mars Habitat Project. Step 3 involved evaluating all four selected VR devices, software, plugins and converting...
the BIM-into-VR model taught by the instructor. Step 4 involved the process of converting BIM models to VR models by the students. Step 5 involved a 5-point Likert scale survey based on the examined students’ perceived learning outcomes and a 10-point Likert scale survey used to evaluate students’ preference level of using each of four VR devices.

All students experienced the four commercially available VR headsets in this study included HTC Vive, Oculus Rift, Acer WMR, and Samsung HMD Odyssey. Table 5 shows the different features of the VR goggles utilized for this survey.

Figure 5. Process of evaluating BIM-into-VR.
Table 5. List of devices used in BIM-into-VR case studies.

|                         | Oculus Rift | HTC Vive | Samsung HMD Odyssey | Acer WMR |
|-------------------------|-------------|----------|----------------------|---------|
| Company name            | Facebook    | HTC      | Samsung              | Acer    |
| Field of view           | 110°        | 110°     | 110°                 | 100°    |
| Max Resolution          | 2160 × 1200 | 2160 × 1200 | 2880 × 1600         | 2880 × 1440 |
| Display type            | OLED        | OLED     | AMOLED               | Dual LCD display |
| Pixel Density           | 456ppi      | 461ppi   | 615ppi               | 706 ppi |
| Weight                  | 470g        | 563g     | 644g                 | 848g    |
| Platform                | Oculus Home | SteamVR, VivePort | Windows Mixed Reality, SteamVR | Microsoft Windows Mixed Reality |
| Headset Type            | Tethered    | Tethered | Tethered            | Standalone |
| Max Refresh Rate (Hz)   | 80          | 90       | 90                   | 90      |
| Multiple concurrent users | Yes        | Yes      | Yes                 | Yes     |
| Controller              | Oculus Touch, Xbox One | Vive controller, PC compatible gamepad | Samsung HMD Odyssey | 6DOF Tracking within HMD Camera FOV |
| Head tracking           | Outside-In Tracking | Outside-In Tracking | Inside-Out Tracking | Inside-Out Tracking |
| Primary input device    | Controllers | Controllers | Controllers | Controllers |
| Portability and setup   | Medium      | Hard     | Medium               | Medium   |

At the end of the quarter, the course lecturer sought the participating students’ opinions regarding the advantages and effectiveness of exercising VR goggles/technology. To illustrate the effectiveness of this system, the instructor presented two different projects as test-models. Figure 6 shows the 2D, 3D, and VR models of the Norris Center building located at Northwestern University. All models were designed by students in Autodesk Revit 2019, one of the major BIM authoring applications, and then converted to VR models by Enscape 2.6.1. This model contains architectural, structural, and MEP models in detail.

In the second case study, as shown in Figure 7, VR allowed students to have a virtual walk-through on the NASA-Mars Habitat model to visualize diverse project setups, compare and examine those setups, and formulate their options for different possible design, method, and material. The workflow of transforming the NASA-Mars habitat project BIM model to a VR viewable model is illustrated in Figure 7. These steps begin with creating and designing a data-rich and comprehensive BIM model by Autodesk Revit software. In this research, students used BIM 360 cloud server/database to store and get real-time access to their models. The next step is to convert the BIM model to a VR model by Fuzor plugin for Revit. Oculus Rift, Samsung HMD, HTC Vive, and Acer WMR headsets were used for this research.
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Figure 7. The workflow of BIM-to-VR for NASA Mars Habitat project.

4. Analysis and Results

All students were surveyed by using a set of questions addressing eight characteristics, mentioned in Figure 4 as (1) Learnability, (2) Interoperability, (3) Visualization, (4) Real-world, (5) Interaction, (6) Creativity, (7) Motivation, and (8) Comfort. The participating students presented numerical scoring that stated their evaluation of each factor’s importance in the BIM-into-VR system. The relative importance index (RII) in Equation (1) is used to compute the significance of the factors that influence the participants learning outcomes:

$$RII = \frac{\sum W}{A \times N}$$  \hspace{1cm} (1)

where $W$ = the weight specified by the students for each factor, ranging from 1 to 5; $A$ = the largest weight = 5; $N$ = the total number of students; and $RII$ = Relative Importance Index.

Table 6 shows the means and the RIIs for the responses. The results indicate that the means of all questions were higher than 3.80 out of 5.00, which can be considered “good”. The survey’s overall mean shows that students are clearly interested in using and would...
benefit from BIM and VR integration. As to the relative significance of the various aspects, the question that sought the students’ view about the degree to which the BIM-into-VR model increases motivation had the highest RII of 0.982. This can be described by the fact that using BIM and VR constantly creates an immersive experience that motivates students to learn effectively. This rationale also supports the second-highest-ranked and third-highest-ranked aspects, i.e., improving the visualization, creativity, and interaction of students (RII = 0.973) and improving Real World (RII = 0.956). Overall, the results indicate that respondents acknowledge the value of using the BIM-into-VR model in AEC education and learning environments.

Table 6. Mean ratings and relative importance indices (RII).

| QN | Evaluation Question                                      | Number of Responses | Mean Rating | RII  | Ranking |
|----|---------------------------------------------------------|---------------------|-------------|------|---------|
| 1  | To what extent can BIM+VR improve your Learnability?    | 0 0 3 4 16          | 4.565       | 0.913| 4       |
| 2  | To what extent can BIM+VR improve Interoperability?     | 0 0 5 4 14          | 4.391       | 0.878| 5       |
| 3  | To what extent can BIM+VR improve Visualization?       | 0 0 0 3 20          | 4.870       | 0.973| 2       |
| 4  | To what extent can BIM+VR improve Real-world?           | 0 0 1 3 19          | 4.783       | 0.956| 3       |
| 5  | To what extent can BIM+VR improve Creativity?           | 0 0 1 1 21          | 4.870       | 0.973| 2       |
| 6  | To what extent can BIM+VR improve Interaction?          | 0 0 0 3 20          | 4.870       | 0.973| 2       |
| 7  | To what extent can BIM+VR improve Motivation?           | 0 0 0 2 21          | 4.913       | 0.982| 1       |
| 8  | To what extent can BIM+VR improve Comfort?              | 0 4 6 2 11          | 3.870       | 0.773| 6       |

Notes: 1 = strongly disagree to 5 = strongly agree; QN = question number; RII = relative importance indices.

The students considered VR systems a learning motivator for design and construction principles. It was also thought learnability, match with the real world, and creativity. The participants regarded the VR technologies to be more engaging and interactive than traditional lectures. Students were happy to use the VR technologies, but they did not always feel comfortable wearing some headsets for a long time (they feel discomfort when moving their heads around). Students must learn several software applications to deal with the interoperability issue, from a 3D/BIM-based model to a VR-enabled model. Additionally, students thought that VR technologies are great for visualizing any architectural model. The survey results regarding their VR technology experience and their evaluation for each VR headset on the list and their preference level are presented in Figure 8 respectively.
A summary of the proposed integration’s strengths and weaknesses in this study is presented in Table 7.

Table 7. Summary of the findings of the BIM-into-VR in AEC education and training process.

| Characteristics | Findings                                                                                                                                 |
|-----------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| **Learnability** | • A new way to learn the design and construction with the human scale.                                                                |
|                 | • Virtual environment to mockup some safety hazards without wasting any materials or cause damage to equipment.                         |
| **Interoperability** | • Easy to convert the geometry and material/texture if we have the plugins (e.g., Enscape, Fuzor).                                      |
|                 | • File size limitation and time-consuming to simplify the detailed BIM model to “just for the show” VR-ready model.                    |
|                 | • Additional time and effort plus the special skillset are needed if we want some interaction reactors (e.g., door opening, crane moving). |
|                 | • Some embedded information (properties of the element) might get lost from BIM to VR.                                                   |
| **Visualization** | • A real-time photorealistic experience with the first-person (gaming) perspective and gravity to visualize design objects with the context rather than the traditional 2D drawings and 3D models from a computer screen. |
|                 | • Daylighting and artificial lighting simulation in VR with immersive walk-through and fly-through experience are phenomenal.         |
Table 7. Cont.

| Characteristics | Findings |
|-----------------|----------|
| Real World      | • Easy to discover some design issues or modeling mistakes during virtual teleportation with eye-level viewing perspective.  
• Provide a real-world context in the virtual environment to review the safety issues like egress, clearance, and traffic maneuver during construction and operation and maintenance phases. |
| Interaction     | • VR is a different learning experience which provides interaction with instructor and classmates.  
• VR live meeting (e.g., InsiteVR) provides a real-time, dynamic design collaboration experience for people around the world to meet virtually.  
• Using the controllers to react something like sketching or dragging the objects inside the virtual environment is a new interactive way of learning. |
| Creativity      | • Gamification is the application of game-design elements and game principles in non-game settings. Students will gain more creativity while using the game principles in their design.  
• However, students might spend too much time focusing on game-design elements but not resolve the real-world design challenges. |
| Motivation      | • VR is a new tool with many different headsets and BIM-to-VR software applications being released each year, which provides a motivation to learn the latest technologies.  
• Gaming effect could be a driver for learning with some excitement. |
| Comfort         | • Motion sickness is a consequence of a delays between natural head motion and a shift in virtual perspective and leads to a disruption in balance. For years, VR was unusable due to the latency gap between vision and headset.  
• Using teleportation instead of walking and turning around inside VR may reduce the motion sickness, but this is subjected to the individuals.  
• In addition to motion sickness, the weight of VR headset, the size and shape of the goggle area (might conflict with glasses), and the texture of holding bend to our head is all the reasons related to comfort.  
• Some people might have sensitive eyes and cannot wear contact lenses. Moreover, bifocal lenses do not work well with VR viewing. Nearsighted vision is varied individually, and VR headset is hard to be custom-made. |

Note: BIM = building information modeling; VR = virtual reality; 2D = two dimensional; AEC = architecture, engineering, and construction.

5. Conclusions and Discussion

It cannot be overstated that it is essential to ensure that future project managers who graduate from AEC programs are fully prepared to use the latest AEC technologies that they will need in their future careers. As the digital computer technological revolution continues to increase in the AEC industry, the impact of their extensive applications for training and educational objectives is of interest. One of the primary reasons for utilizing BIM and VR as educational technologies is that they come across young students experientially. The traditional educational approaches need to add engaging and real experiences that will drive successful learning. However, having this virtual educational environment requires students to understand the process, devices, platforms, and software used in AEC projects. VR can provide this element and its visualization of the real environment is very close to reality. VR allows simulating dangerous, expensive-to-access, and hard-to-reach environments. Due to VR characteristics and features, its applications may enhance creative and imaginative thinking. It can improve the learning process and motivate students to develop necessary skills for success and innovation. VR has the potential to improve...
traditional approaches with interactive simulations and stunning visuals that immerse students in genuine learning experiences. It can push the limits of the old-fashioned classroom to be appealing, inspiring, and responsive to the student’s needs.

This research’s motivation came from the importance of VR technologies in the AEC education environments and their potential to improve students’ learning performance. In this research, a summary of worldwide movements regarding BIM and VR in AEC training and education has been conducted, and the technologies, application areas, and future research directions have been identified. This study focuses on using BIM and VR technologies in AEC education and training in the classroom and how these technologies can improve student grasp of all aspects of AEC concepts. As a primary stage, this research first did a comprehensive review regarding BIM and VR and their integration in the AEC industry to highlight the industry’s requirements to apply them in AEC education environments. This research developed an IDEF0 model to show best practices for integrating the BIM model into VR technologies. Moreover, it explains the inputs, controls, mechanisms, and outputs of each process in the BIM-to-VR workflow. The BIM model’s development into VR technologies is transitioning from desktop-based systems to mobile ones with enhanced immersion and interaction abilities. Such developments have benefited many AEC domains and stakeholders, and it needs a root development from students. Given the potential of BIM and VR for situated learning, the authors reviewed previous studies that discussed BIM and VR technologies in the AEC training and education environment. They evaluated this integration by collecting feedback from students in the MPM program of the Civil and Environmental Engineering Department at Northwestern University. Through a comprehensive questionnaire, the students were asked about various factors that affect their education quality. This research evaluated the performance of the different BIM-into-VR environments and their impact on students’ learning performance aspects (Learnability, Interoperability, Visualization, Real-world, Interaction, Creativity, Motivation, and Comfort) within two projects, one involving the “NASA Mars Habitat Project” and the other involving the “Norris Center Project”.

VR in the AEC industry bridges the digital data in BIM to a more understandable shape and scale for students. As the technology quickly moves to the mainstream, faculty in the AEC areas have started to embrace VR due to its enormous education promises. VR is beneficial for generating interest and motivating student participation; assisting imagination and enabling visualization of complex models that are not possible in traditional classrooms; and providing several opportunities, such as increasing students’ interaction with instructor and classmates, which improve the quality of education. If the VR-associated hardware and software could be more affordable and accessible to all students, it can play an essential role in distance learning during the COVID-19 pandemic period. More and more universities are doing digital transformation while students are complying with the stay-at-home order.

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