INTERACTIVE VIRTUAL CONSTRUCTION

A Case Study of Building Component Assembly Towards the Adoption of BIM and VR in Business and Training

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Abstract. Present day building product manufacturers face difficulties in scaling businesses. Key decisions surrounding technology adoption are typically measured against feasibility of use and long-term profit. Building Information Modelling (BIM) and Virtual Reality (VR) provide the potential for teaching building product assembly to employees and construction contractors. This eliminates the need for deploying training personnel to job sites, reduces manufacturing carbon footprint and wastes in product samples required for training. VR content development is difficult and performance within VR applications must be near reality in order to improve adoption of such technology through training. This exploratory study investigates important factors that enhance adoption in business cases through training. We developed an innovative BIM+VR prototype for SwiftWall; a temporary wall manufacturing company, highlighting rigorous processes for in-house BIM anatomy and VR development. This paper provides a step-by-step approach to replicate the prototype. The prototype was tested in several demonstration sessions. The approximate time to install 40 linear feet of SwiftWall is 30-minutes at the simplest level. This timing is equivalent to 28 linear feet installation in 21-minutes achieved with the BIM+VR prototype demonstration. The matching timing results show a significant potential for adoption in business, improved sustainability and employee training from a time and cost-efficient standpoint. Concerns and key issues from development to deployment are discussed in detail. The BIM+VR virtual construction prototype provides adoption potential for training remote partners thereby increasing possibilities of SwiftWall scaling to distributors and product carriers across a larger geographic region.

Keywords. BIM; Virtual Reality; Unity; Training; Game Design; Construction Assemblage; Construction Material; Virtual Construction; SDG 9.

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1. Introduction

New technologies such as E-commerce, Big Data, internet of things (IOT), Artificial Intelligence (AI) all provide disruption potentials for business landscapes. However, design and construction firms are still struggling on how best to harness them (Syamimi et al., 2020). Virtual Reality (VR), which is fast gaining ground, has become an essential tool for the transfer of knowledge in educational settings (Alizadehsalehi et al., 2021; Bashabsheh et al., 2019; Caesaron, 2017). On the other hand, in most industries, there are identifiable adoption barriers that stifle the successful implementation of such technologies. Such barriers span from corporate strategic alignment, talent retention, market fragmentation to sales or growth projections (Cacho-Elizondo et al., 2018). Brands in the design and construction industry are racing to catch on the Virtual Design and Construction (VDC) trends to gain competitive advantage. Frustration and abandonment of adoption strategies may occur at various levels of an organization if proper understanding of diverse platforms and phases required for adoption is not achieved. It has been established that the visualization power of VR affords clients the abilities for rapid decision making (Tariq et al., 2019). VR apps, demonstrations and games are currently created by professional designers, thereby making the skillset required a very niche one (De Regt et al., 2020) hence the adoption dilemma. For big firms, a large opportunity is identified in communication between workforce and also in improving manufacturing processes, (Bosché et al., 2016; Fernandes et al., 2006).

This research provides a step-by-step approach to the development and adoption of Building Information Modeling (BIM) and Virtual Reality (VR) in a case study for building product manufacturing business; SwiftWall, located in Michigan, USA. We seek to understand BIM and VR adoption techniques highlighting use cases that contribute to success rates for small and medium size companies. A BIM+VR prototype was developed for this purpose, highlighting best practices for content development and usability.

2. Background Study

There is a need for more extensive research work regarding the adoption of VR in teaching architecture with a potential to providing better design understanding for students beyond the traditional methods (Bashabsheh et al., 2019). There are also limitations in adopting BIM and VR in construction safety trainings with drawbacks in large-scale adoption although mobile VR provides improved portability for job sites compared to PC-based VR . A paradigm shift is required to transform the construction industry from a craft-based one to a knowledge and value-driven industry (Goulding et al., 2012). Innovative and flexible training options are essential to drive the transformation. Beyond the technology, on a larger scale, several factors that limit rates of adoption have been identified by a study (Fernandes et al., 2006). Such factors include, for instance, top management support, internal needs, degree of competition and champion within a company. This study however, was limited to the UK construction industry and its results may vary widely across other geographic regions like the United States where business practices, market size, access to technology, resources and funding are largely different. Results from other sectors may provide variables to these factors if compared. Conventional methods of operation at SwiftWall include issuing quotations and basic 2-Dimensional drawings alongside image annotations to customers. There has been a need to cut down on manufacturing wastes, improve productivity and sales for upwards business scaling for training distributors and installers across various regions.

2.1. REQUIREMENTS FOR VR ADOPTION

There are technical and financial decisions important for the adoption of VR in business cases. There is limited evidence to support claims regarding skill levels of project teams being a major determinant for adoption, however, cost is a major factor for decision as financial experts have more decision making power than technical experts within a company (Fernandes et al., 2006). End users also provide clarity regarding needs thereby increasing the possibilities of adoption. This factor alone, is a big component in the overall scheme of this BIM+VR research. For the purpose of adoption for training, real construction projects are peculiar in nature and require different tasks which may have varying results in terms of cost and time implications. As a result of cost overruns, delays and errors associated with training on real projects, real project environments have been simulated in the past to address this. These training simulations allow for safety with little or no impact on project performance (Bosché et al., 2016).

For the development of BIM and VR, there must be a balance between data required for use in a VR model and the level of performance required for an optimal experience. This often requires culling objects, simplifying geometry, and improving object face. Unity provides entry level game development for novices who can use its pre-loaded asset store for content development (Foxman, 2019).

2.2. GAPS IN RESEARCH

Although VR research has been extensive in theoretical spectrum, there is limited research addressing problems encountered in development for adoption using a business case study. Previous research has focused on cost, installation time and high risk as major factors of non-adoption (Fernandes et al., 2006). Current BIM and VR workflows are limited. There is an increasing need for researchers in academia, industry, hardware and software developers to collaborate for improved and established workflows (Alizadehsalehi et al., 2019).

Four major problems were identified in this study for the business and training case. They surround upward business scaling with products, processes and people viz -

- Cost of building prototypes – physical product prototypes are costly. This research proposes a simplified virtual product prototype development process.
- High risk of safety & high cost of staff deployment – Our research proposes a safer training use case in a shared remote environment.
- Cost of adoption – BIM and VR content development is difficult and costly if poorly executed. Our research highlights optimized business use cases for SwiftWall.

As shown, cost is a major determinant in business operations and sustainability, and therefore, proposed solutions must be cost-effective. This research does not address directly the costs of the adoption of BIM+VR technology as it has been explored in previous research (Fernandes et al., 2006). In VR training applications, purposes are specific and are typically equipment, machine or process operation based. It is established however, that the development of such training content is challenging (Motejlek & Alpay, 2019). We highlight the development process for content development for improved usability thereby providing a manufacturer-specific business use case for adoption in SwiftWall.

3. Methods

This exploratory case study proposes a two-phase approach to adopting BIM and VR in the SwiftWall business environment. The first stage covers prototype development while the second phase demonstrations and findings.

The inclusion of detailed virtual models is an essential part of the VR experience to mimic real-life situations and assembly sequence. To achieve improved realism, various components like tracks, channels, panels and accessories were modelled in real scale and matching product texture. As indicated in previous research, it is important to work closely with industry to accurately model situations that are peculiar to processes, controls and responses in the field in order to improve interactive learning (Anifowose et al., 2022; Xiao et al., 2004). Six different departments were contacted for development direction input. Experts totalling thirteen from all departments; Architecture & Engineering, Production, Installation, Sales, Training, Safety discussed essential milestones for successful product development in VR. Management input was sought for business integration after demonstration.

3.1. BIM+VR PROTOTYPE DEVELOPMENT

Digital BIM models of various SwiftWall components were developed to high level of detail 400 i.e. fabrication-ready geometry which was important for visual and dimensional realism of the assembly process.

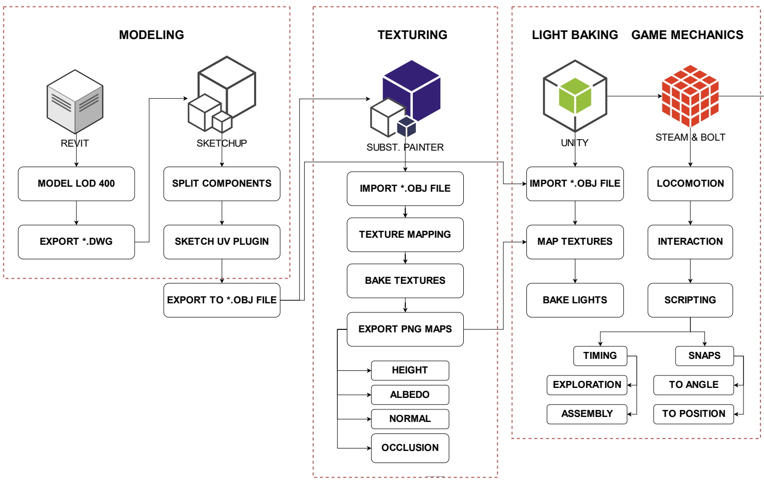

Figure 1. Prototype Development & Software Workflow

Revit 2020, Sketchup 2019, Substance Painter 2019.3.3 and Unity 2020.1 are readily available licensed software tools used for the prototype development shown in Figure 1. SwiftWall components were modelled in Revit, exported and optimized for geometry in SketchUp and converted to *.obj files. This allowed the retention of geometry details and UV (axes) mapping based on the material files. These digital models with their corresponding spatial properties and scale were imported into Substance painter. Unity game engine was used to develop the components in VR. These tools provided the most optimized methods for visual details and performance. A mock-up of an airport lobby; the most common product usage scenario was developed to mimic real life application. As shown in Figure 2, a staging area allows users to setup various wall configurations after inspecting a ready-made wall configuration. Stacked components are made readily available within the environment for use and the player/user has an in-game time to monitor how long they have been completing the assemblage task in VR.

To prepare the prototype for modelling and lighting, SwiftWall components were carefully modelled from real photographs and dimensioned CAD files. The file exchange process between software is extremely important for successful execution. Optimized geometry and file export format for precise geometry and faces was *.obj file format, among all file format types tested. In an installation environment for a factory with lower levels of lighting, a similar level of lighting must be achieved to increase realism. Installation of SwiftWall products in an overly bright scene can lead to visual discomfort also as the panels are bright in colour. Downlighting at higher levels and reflection probes at mid-level were located to replicate realistic lighting especially for the task assemblage area.

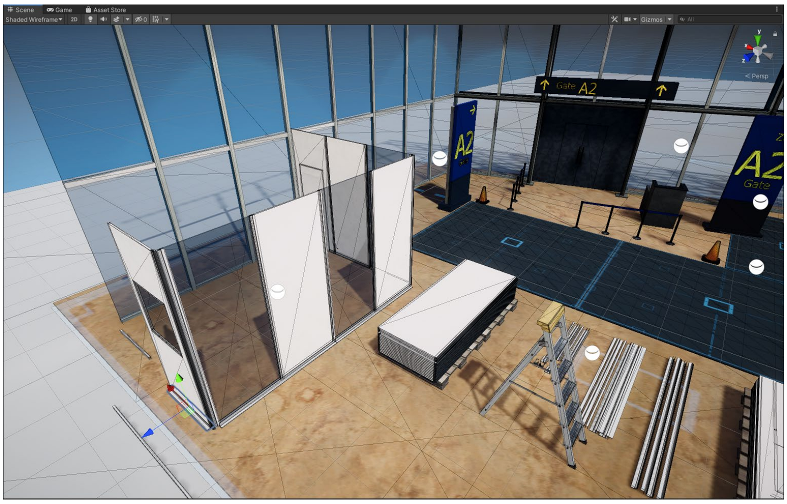

Figure 2. SwiftWallVR Prototype: Virtual Construction Scene Setup

The model's texturing process was completed in Substance Painter software to achieve near-realism product representation. However, for optimum texturing results, object faces were unwrapped to receive scanned texture projections on each face using SketchUp and SketchUV plugin. Previous related work in our research lab (Anifowose et al., 2022) has explored various impacts of good texturing towards improved realism. Various texture channels are combined to improve baking results. The ambient occlusion and roughness texture channels increased visual clarity in the scenes.

3.2. PROTOTYPE DEMONSTRATION

Several demonstration sessions were carried out by three (3) users who are experienced installers and thirteen (13) department representatives in attendance. Recordings of the demonstration sessions in Figure 3 are stored in a safe storage and can be retrieved for future analysis. We considered specific content integration techniques and developing VR interaction features aimed at improving the overall VR experience. In order to make the prototype usable for first-time VR users which is suspected to be most of the population in future user studies, features such as an in-game timer, snap-to-position and snap-to-angle are incorporated. These features are overall intended to improve user engagement for better learning outcomes in a training use case. As highlighted in previous works on VR, integrating text into virtual environments is important for users to read (Xiao et al., 2004).

Figure 3. Demonstration setup for BIM+VR Prototype at SwiftWall Innovation Center

To measure effectiveness in training, a timer was developed in-game to allow time tracking of tasks for various stages. The first stage, which features a new user exploring an already-built SwiftWall assemblage counts down onboarding time. Thereafter, timing commences for the assemblage execution where the user builds walls of different configurations. On a corporate level, this can be compared with average install times. A timed assemblage match was achieved between the BIM+VR optimized prototype and physical SwiftWall assemblage. Video demonstration can be found here - https://youtu.be/Qt4Om4MMt4E.

4. Experimental Results & Discussion

This section will explain opportunities and limitations based on the BIM+VR prototype. Stemming from the real scale objects to human body ratio in the VR scene, near reality discomforts are reproduced as physical body adjustment must be made to complete VR actions. Installers typically carry the long-sized panels on their sides with directional vision obscured by the sheer size of the panels. This requires users to carefully manipulate objects while also being conscious of virtual movements and directions for successful installation. There is a safety risk in on-site training that decreases in VR. A BIM+VR training prototype, however, is not just less risky but it also prepares the user for a real on-site scenario, providing a much smoother transition from a safe training environment to a riskier and chaotic construction site.

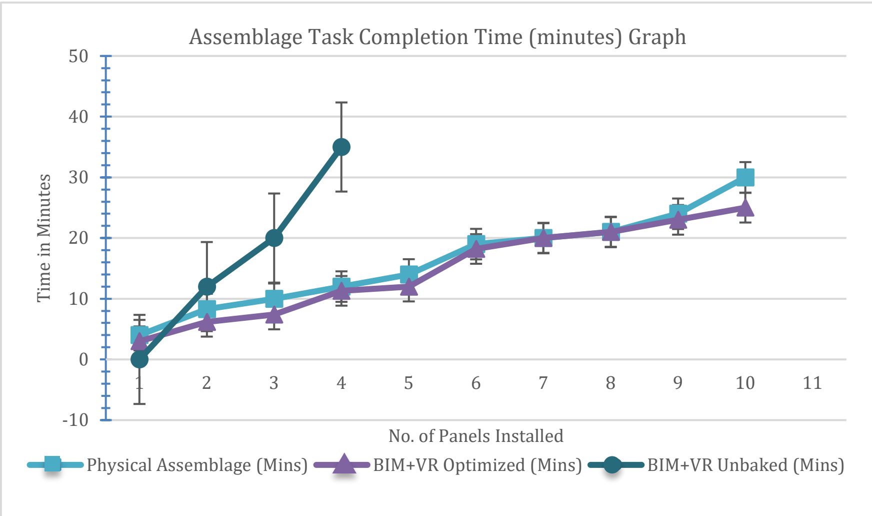

Figure 4. Graph showing matched completion time between physical and BIM+VR assemblage

In this section, results from the development process are first discussed. The BIM+VR prototype was rigorously developed to simulate realism in geometry, materials and product features for example, the proprietary tongue and groove system in SwiftWall Assemblage. The texturing for Acrylonitrile butadiene styrene (ABS) skin material was scanned before applied to the geometry thereby increasing realism. Visual comfort was further attained by texture baking with Ambient Occlusion. During the preliminary tests and early stages of development, without the baking, visual comfort was not achieved in unbaked scenes. This led to higher task completion times as users struggle with visual precision; in one case, 35 minutes was spent on 12 linear feet installation in VR which could negatively impact its adoption as indicated in Figure 4.

The approximate time to physically install 40 linear feet of SwiftWall is 30-minutes at the simplest level. Using a Distance/Time calculation, this provides a Constant K of 1.33 (linear foot of SwiftWall installed per minute). A similar installation time match for 28 linear feet (7 panels) was achieved in 21-minutes (average timing result from the three installers) in the optimized BIM+VR prototype. On the contrary, the unbaked scene produced higher installation times and higher levels of visual discomfort. With an increased level of realism, the assemblage task can be completed as the user makes more precise judgements of object placement based on interactions. We acknowledge that the installation time results can vary if the difficulty level of assembly is higher or lower. Since this is possible, the next phase will feature flexibility in game level difficulty in order to train participants from easier to more difficult assemblage scenarios.

4.1. LIMITATIONS

One of the key concerns is the current availability of development hardware. A large percentage of hardware are consumer grade which create a challenge for rigorous development endeavours (De Regt et al., 2020). There are also performance limitations that slowed down development due to model complexity of the game scene and the available hardware . Deploying a BIM and VR solution is known to require high performance hardware beyond model optimization (Sampaio, 2019). Product innovation and BIM+VR development rate must match in order to be successful. If product innovation outpaces updates and development of the BIM+VR system, there are high possibilities that such systems might become obsolete very quickly. This may necessitate redevelopment thereby increasing adoption business cost and hindering long term sustainability.

4.2. ADOPTION MATRIX

Time and cost benefit analyses were derived from the BIM+VR prototype development thereby providing a case for management and financial decisions to be taken regarding the route for adoption in the business workflow and future scaling. Two classes of use cases were highlighted below:

- Internal Use Case – Internal design team and internal employee training.
- External Use Case – External architect use case, single partner training (no support), remote partner training (with multiplayer support) and consumer use cases.

After several demonstrations to in-company representatives, discussions surrounding adoption was undertaken in a 13-person vote style consensus from department representatives. Using development/deployment cost and business scaling benefit analysis, the most viable option for adoption was a single partner training. We believe that the BIM+VR prototype provides SwiftWall the best opportunity to train their partners and grow business rapidly. Internal employee training was the next most preferred adoption method based on costs and perceived benefits. Consumer use case was the least desired as the cost of deployment and benefits will not serve the business' scaling purpose.

5. Conclusions and Future Work

From a technical standpoint, the highlighted processes for developing the prototype in this research provides an easy entry for any organization or research group intending to develop VR prototypes for construction assembly. We have successfully designed and tested VR precision features such as snap-to-position, snap-to-angle, texturing, baked lighting and time tracking to improve training. These features have not been previously studied towards BIM & VR adoption within the research community. This research has also identified the most preferred business and training use cases towards adoption using SwiftWall as a case study business.

This type of research and development help manufacturing companies achieve sustainability goals by reducing manufacturing wastes and production carbon footprint. The development processes highlighted in this research and adoptable by future researchers include -

- Accurate product modelling, best file exchange formats and software workflow.
- Unwrapping geometry face for accurate UV texturing to improve realism by texture baking.
- Improving user visual comfort & task performance with optimized baked lighting.

A first barrier to BIM and VR adoption is the lack of education and training. A lack of BIM expertise within an organization limits in-house development capabilities of BIM+VR. Management must make decent strides in employing new hands or educating existing employees about their products and BIM systems. BIM trainings could be made prerequisite requirements for product design teams and employee onboarding process. To further improve performance & adoption, the next prototype release scheduled for the user study has been designed to include text instructions for easier sequential installation.

Building a prototype of this nature outweighs verbal conversations surrounding adoption. Developing details and increased realism can lead to improved usability based on near-reality experiences. The process presented in this paper showcases a novel approach to establishing grounds for adopting BIM and VR prototype (product) as part of the business scaling strategy (process) while transforming how employees (people) and prospective partners are trained. By developing a prototype, a business use case is identified, and the people are emotionally subscribed to adopt the technology as the value added to the chain becomes obvious. In a future study, users will be invited to test the prototype upon approved Institutional Review Board (IRB) number IRB2022-0057. Assemblage completion times will be measured and compared with a physical task assemblage.

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