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Virtual Reality (VR) Integration With Practical Building Information Modeling (BIM), Enhancing Interior Design Experience.

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ABSTRACT

This study explores the integration of virtual reality (VR) in enhancing building information modeling (BIM) processes of visualizing the final product, drawing insights from previous applications of VR to improve client engagement and project efficiency focusing on the interior aspect. The research demonstrates minimal costs associated with training and VR headsets, leveraging free Unreal engine (UE) plugins. The implementation of Transform client interactions, offering immersive experience that facilitate a deeper understanding of spatial dissensions and design elements. Furthermore, the research discusses the dimensions of BIM maturity, highlighting how VR can serve as a catalyst for accelerating BIM adoption.

Keywords: (BIM) building information modeling, (FOV) field of view, (VR) virtual reality, (FPP) first person perspective, (UE) Unreal engine.

1. Introduction

In a search for the optimum use of today's technology and its applications, targeting the countries which are still in the early stages of BIM, presenting an essential element for using virtual reality in visualizing the 3D BIM models and the surrounding environment, achieving advanced simulation from the cold, emotionless 2D rendered images and video animations on a flat screen. The main objective is using the cheap and available tools, to connect the stakeholders in a new way minimizing the error gap and presenting the final product to the clients in an interactive and engaging style, allowing for a real-time Feedback. With the early stages of BIM, when we present such style of visualization, it will be an advanced step in maturing BIM in the targeted countries, and creating a new creative roles in the BIM frame work, aiming to get the attention of the market and investors through presenting not only the exterior models, but also the interior design, advancing the experience beyond static. In today presentations of interior design projects, we are often unaware of how our interior environments impact us on a subconscious level because of how we are presenting the final product (images-videos) without a clear context" Design without context liquidates meaning" 2, and in some cases it can be misleading. Moreover, elements such as lighting, texture, and spatial layout can be felt in a VR/AR world. The psychological effects extend by immerging into the screen and explore, as the real key of design and architecture propose." the success of setting up interior architectural design with active psychological conception judged by how the design fulfills values, needs, preferences and satisfactions of users." (1).

1.1. *Research questions*

1- How does the integration of VR improve the visualization of 3D BIM models? . this aims to explore the new options with using the VR compared to static 2D methods.
2- What is the psychological impact of VR on the client awareness of the interior design projects? , to understand how VR influence subconscious response to the design elements like lighting, texture, and spatial layout.
3- What are the pros and cons in utilizing gaming engines (Unreal Engine), for BIM visualization in the heavy market? , seeking to identify the full potential of using an accessible gaming technology in BIM applications
4- How can implanting VR enhance the client engagement and feedback during the design process? , the role of VR in facilitating real-time interactions

and feedback

5- What impact does the engaging and interactive visualization have on the maturity of BIM in the developing countries? To examine the overall development of BIM in the targeted region after adopting these techniques.

1.2. Research problems

We can focus on a different aspects of integrating VR with BIM , one key aspect of interest, is the effectiveness of this integration in enhancing stockholders communication and understanding compared to traditional modeling methods , additionally the market value of the advanced rendering and visualization techniques, regarding the market acceptance and attracting new investments .another critical issue is the psychological impact of VR on user experience in the interior design assessing how immersive environment and surrounding affect the client.

1.3. Research Aim and goal

The exploration focusses on VR/AR technology in visualizing final BIM models for countries in the early stages of BIM adoption. Aiming to enhance stakeholders' communication through interactive experience. Seeking also to minimize communication errors among the teams, improve client's feedback, and contribute to BIM maturity, by using accessible tools like gaming engines and VR headset. Ultimately, the goal is to create new roles withing the BIM framework and attract investment through user-friendly rendering and visualization techniques that effectively showcase the BIM models.

1.4. Objectives

1- Analyze the psychological effect of VR on the client's perception of the projects. Approximately a normal person needs 5 to 10 minutes to read a 100m architectural floor-plan on papers, in the other hand the same person needs 10 to 20 minutes to explore the same floor-plan in VR providing a deep understanding of the space and interacting with its elements creating a personal embedded connection.

2- Enhancing stockholder's engagement, for optimum resources use. interacting with the model in real-time making immediate adjustments and decisions you can streamline discussions and decision-making process further reducing meetings duration by an estimated 20% to 40%

3- Assess the influence of interactive visuals on BIM maturity level. The phases to transition from level 1 BIM to level 2 BIM using VR will take -approximately- 5 to 11 weeks allowing for adequate training, preparation, model integration, testing, and stockholders interactions. After that time investment, the project deliveries will be more efficient in the long run.

4- Evaluate the use of gaming engines for BIM visualization, utilizing cross-pathed industries techniques. "The overall implementation framework revolves primarily around the iterative Design-Play approach where a user of the system creates or loads an existing architectural model into the BIM modelling software, enters into a real-time game environment containing the model and its associated information, and evaluates the design."[2]

5- Determine the cost-value and accessibility of VR tools. While the upfront cost of the integration can be significant ,the long-term benefits in efficiency, error reduction and client satisfaction can provide an upper value.

2. Literature review

The integration of VR and BIM emerged as a transformative approach in interior design, offering new fields for visualization, collaboration and decision making. as the complexity of architectural projects increases, traditional design methods often fall behind in effective communication and design ideas deliveries . (Wang et al., 2019). By offering this experience we are allowing stakeholders to interact in real-time focusing on a deeper understanding of design concepts and collaboration among team members (Kwon & Lee, 2020). We aim to pair current research and insights on how VR-BIM integration is enhancing the architecture practices focusing on the interior design side, while also identifying the obstacles.

2.1.1. *Current state of VR and BIM in interior design*

VR opened a new way for interior designers to present their work, by allowing for three-dimensional experience of the designed spaces. BIM on the other hand provided a digital representation of the physical and functional characteristics of a building. The integration enabled more accurate visualizations and efficient project management. The adoption of VR and BIM has been growing, driven by the need for more efficient design processes and enhanced client communication. However, the integration varies across the industry, with larger firms being early adopters due to the initial investment required.

2.1.2. *The effect of VR on BIM collaboration*

The VR-BIM integration allowed a multiple users to work within a shared virtual environment ,improving collaboration and a better understanding of the design. (M. Johansson, M. Roupé,). simultaneous interaction with the digital model enabled a real time discussion during design review and planning, minimizing distractions helped identifying logistical challenges and potential issues before they arise on site .

2.1.3. *Advantages of VR-BIM integration in interior design*

The primary benefits of the integration are the significant enhancement in the visualization capabilities. the integration allows designers and clients to experience spaces in a highly realistic and immersive manners and gave the ability to virtually walk through and interact with a design space before it is constructed, leading to better understanding of spatial connection and design elements.

Another important subject is attracting new investors through several key advantages. When we present a project using advanced technology like VR , we reflect that the project is team is innovative and forward thinking. With the identifying potential issues early in the design process, reducing the risk of costly changes during construction, we can reassure investors that their investment is been managed efficiently and effectively.

2.1.4. *The key of a simple yet effective integration is using "game engines"*

Since the beginning of the computerized renders and designs, there was that urge to achieve the most realistic versions seeking for a photorealistic quality, aside from the architecture industry, gaming industry took the same path for reaching the realistic style through a fascinating journey reflecting technological advancement and artistic innovation from utilizing 2D sprites and basic color palettes to photorealistic visuals showcasing the lighting ,shading and textures . Until today game graphics continue to be developed with the use of ray tracing and VR, seeking realism and player immersion. (Swati Atreya et al 2022). The use of gaming engines such as Unreal engine (developed by Epic games) in architecture allow us to fully utilize its tools, such as the VR capability and the rendering engines. Furthermore, today the accessibility of this technology is likely to elevate architectural visualizations allowing smaller firms and independent architects to produce high-quality graphics in their projects.

2.1.5. *Challenges and limitations*

Despite the VR visual in BIM and the ability to attract more investors

High cost: The adoption of VR requires significant initial investment in hardware and training. This can be a barrier, particularly for the smaller firms.

Training: stockholders need training not only in operating the hardware and software but also in using and manipulating VR models within the context of BIM.

Adoption and workflow changes: the shift can face resistance from stockholders, overcoming this issue is crucial for successful implementation.

Table 1 VR visualizations compared to 3D renders (Lee et al., 2023; Brunet & Andújar, 2015; Blascovich & Bailenson, 2011 and Brunet & Andújar, 2015)

Aspect	**VR Visualization/3D Rendered Pictures**
User Engagement	Users report higher engagement levels with VR for data visualization
Data Comprehension	Users report a significant improvement in understanding complex data when using VR environments. VR provides immersive and interactive experiences that enhance the comprehension of intricate datasets.
Preference for Interaction	Users overwhelmingly prefer interactive VR experiences over static images. VR allows for a more engaging and immersive interaction with data, which enhances user experience and satisfaction.
Realism Perception	Users perceive VR as providing a more realistic representation of data due to its immersive and interactive nature.

3. Methodology

3.1. Research methods

By implementing a hypered approach, we used case studies analysis with prototyping to present comprehensive insight on this integration. The analysis of the case studies involved the impact of interior design and how the individual can understand and evaluate the space and its surroundings, whether physically being there or in a virtual environment, in addition the derive of best practices of BIM technology in construction or rehabilitation/demolition. Building upon the foundational information gained from the case studies, we move to the prototyping phase, by developing a simulation to be a quick showcase of VR and BIM integration, allowing us to explore its capability and refine its design based on the feedback and testing.

3.2. Case studies

3.2.1. *The Edge,*

Fig. 1. The Edge facade, Amsterdam, "Ronald Tilleman"

serving a significant study for the integration of BIM and VR. the project shows how the advanced tools can enhance the design, construction, and operational stages of a building . the key features include the followings:

1- BIM application: the project utilized BIM to create a comprehensive model of the building, the model served a core for all the project data, facilitating collaboration among all stakeholders.
2- VR application: VR provided immersive visualization of the design. the stakeholders, including architects, engineers, and clients, could use the VR headsets to explore the 3D model of the building in a virtual environment. this experience allowed users to navigate spaces, assess design elements and a real time collaboration, multiple users could enter the same virtual environment, allowing for interactive design reviews and enhancing communication.

3- collaboration and communication: The integration of BIM and VR paved the path for modern and improved collaboration among stakeholders, leading to refined final product.

located in Amsterdam, (https://edge.tech/buildings/the-edge) referred to as the worlds smartest building,

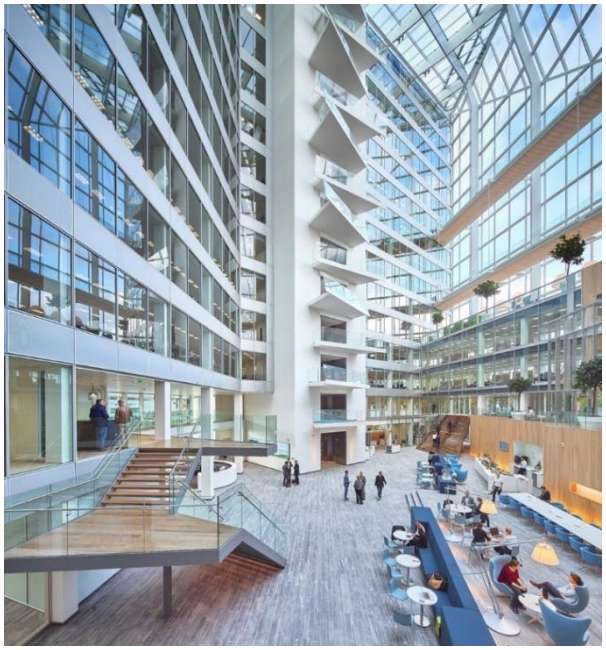


Fig. 2. The Edge, main hall interior, Amsterdam, "Ronald Tilleman"

3.2.2. *V&A museum*

V&A museum of design, the Victoria and albert museum, particularly with its Dundee branch, has embraced BIM and VR technologies, this integration showcase how a modern technology can improve architectural projects , especially in a complex environment such as museums.

Fig. 3. V&A museum of design exterior, "Hufton Crow"

The BIM application represented in:

1- Complex structural design. which allowed the team to create detailed 3D models that accurately represented the museum's complex structure
2- Visual presentation: BIM enabled the visualization of the entire project allowing stockholders to see how different components fit together
3- Emission: the project implemented a low carbon strategy and BIM played a crucial role in it. By simulating energy performance and materials usage, helping in a decision making aligned with sustainability goals.

VR application enhanced both the design process and the visitor experience by utilizing:

1- Design review, VR allowed architects and stockholders to immerse themselves in the 3D models of the museum, facilitating a real-time design review enabling the team to identify a potential issue and gather feedback more efficient.
2- visitors' engagement: by creating virtual tours and interactive parameters/objects, offering a unique way to experience its collections and making the overall experience more engaging.

The integration of BIM and VR in this project demonstrates the potential of technology and experience of arts and design.

3.2.3. *Sagrada Familia – Antonio Gaudi basilica*

Fig. 4. sagrada familia interior Figure 6. sagrada familia, VR environment testing, "blog.sagradafamilia.org"

The Sagrada Familia is a top ten global tourist destination, a UNESCO World Heritage Site and an icon of Barcelona. Weathering the storms of the Spanish Civil War and damage to Gaudi's original plans during a 1936 arson attack, the church continues to rise, speeding up through the decades as technology improves. The BIM gives the tools to make construction on sites like this more efficient and accurate. Improving the process of building or restoring heritage sites makes you a part of preserving human history, cultures and identities, and it's an example of how you can pursue your passion with your BIM skills. Thanks to BIM technology, more people will get to see Gaudi's most famous work fully completed.

Fig. 5. sagrada familia interior "blog.sagradafamilia.org"

Another type of technology being used at the temple, which saves us time, is VR. Today, the Sagrada Família uses the most advanced systems in the world to help its team of architects working on the final designs for Gaudí's project. This way, the model they are developing can be sent to virtual-reality glasses at any given time. The system creates a virtual view of the 3D model the architect is working on and they can see it in the VR headset in under two minutes. This allows the architects to quickly check the volume, geometry, texture or light on a specific element they are designing.

3.2.4. *Sydney opera house renovation*

An iconic symbol of Australia has undergone significant renovations to preserve its architectural integrity and enhancing its functionality.

Fig. 6. Sydney Opera House Concert Hall Renewal, Martin Mischkulnig

In this case the integration of BIM and VR has been pivotal in the renovation process, ensuring the project meets modern standards with respect to the original design by architect Jorn Utzon. The renovation goals is, improving structural integrity, enhancing the visitors' experience and upgrading the facilities to meet the growing demands and to cover the performance and safety standards.

BIM implementation:

1- Creating digital twin: the reno project started with creating a digital twin of the Sydney opera house using BIM, involving detailed 3D modeling of the existing structure, capturing its complex geometry and details. The digital model served as a comprehensive reference for all stakeholders involved.
2- Coordination: BIM facilitated and enhanced the collaboration by using a shared digital model, teams could work together more effectively minimizing delays and reducing the costs associated with the rework
3- Heritage preservation: given a historical impact, the renovation required careful consideration of its heritage aspects, BIM allowed the team to analyze the building original design and materials, ensuring that any updates or modifications were in the preservation guidelines
4- Facility management: post-renovation the BIM model will serve as a valuable tool for facility management ,providing detailed information about the building systems ,enabling efficient maintenance and operation .

VR implementation:

1- Immersive design review: stakeholders could use VR headsets to explore the digital model, allowing them to experience the space as if it was finished. this experience facilitated better understanding and feedback on the design elements.
2- Public engagement and education: by creating virtual tours of the opera house, visitors can explore the building history and architecture interactively. this educational aspect not only enhances the experience but also motivates a deeper appreciation for the culture significance of the opera house
3- Training and safety simulations: VR utilized for training construction workers and staff by simulating the construction processes and safety scenarios in a virtual environment so the staff could gain valuable experience without any risks.

The renovation project showed a successful integration of BIM and VR and how the project team was able to enhance collaboration, preserving the building heritage, improve the visitor engagement and aspects by immersing into the spaces and details of the design , with a 360-degree immersion allowing to navigate through the opera house architectural details and design elements ,as if you were physically present.

3.3. Prototyping

3.3.1. *Introduction*

The practical part of this paper includes finding a prototype/plugin to facilitate the integration with the gaming engine. The plugin export the 3D models from Revit and import it with the materials and elements properties, not effected to use it later in the project ,the second step is the procedure to insert the requested materials and specific environment in the end of step two we should have a finished compatible 3D models in UE awaiting to apply next step, which is to add the modifiers of first person perspective on the project to create the routes, creating the routes before applying

the VR modifiers is a crucial part were you have to design a track that serves a specific purpose, including tracks for the exterior ,interior, and MEP models .after finishing the routes and tracks for the project we can transfer to a VR template suitable for our project including visual reference for all the elements to spur an engaging environment ,connecting the real part of BIM with the excitement of discoveries and examination for a new spaces. To make sure that the project is ready to be launched, multiple users tests should be conducted, after that we can export the files with the types that serve the different platforms (windows, android, iOS).

3.3.2. *Importing a file from Revit to UE*

• Step 1: prepare your Revit model

- Open the Revit project: make sure your model is complete and ready for export.

- Optimize the model: before the exporting, consider simplifying the model and remove unmercenary elements or details that may not be needed in UE environment

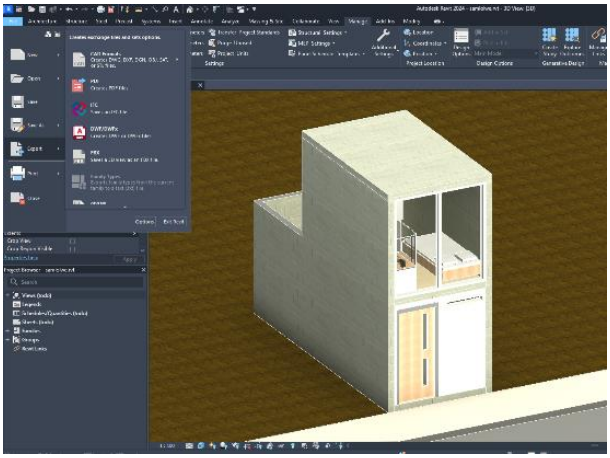


Fig. 7. Revit exporting

• Step 2: using Datasmith plugin:

-Install Datasmith exporter: in both UE and Revit (https://www.unrealengine.com/en-US/datasmith/plugins)

-Export the model: in Revit go to Datasmith tab that appears after the installation of the plugin, click on export and chose the file location the file type will be (.udatasmith), settings can be adjusted during this process like level of tessellation.

• Step 3 : importing to UE

- Datasmith tab in UE toolbar, click on import Datasmith and navigate to the saved file location .

• Step 4 : modifying the scene

- editing materials and settings

-optimizing, by using the Dataprep graph to optimize the model or replacing specific materials and setting up a configuration.

• Step 5 : finishing and tests

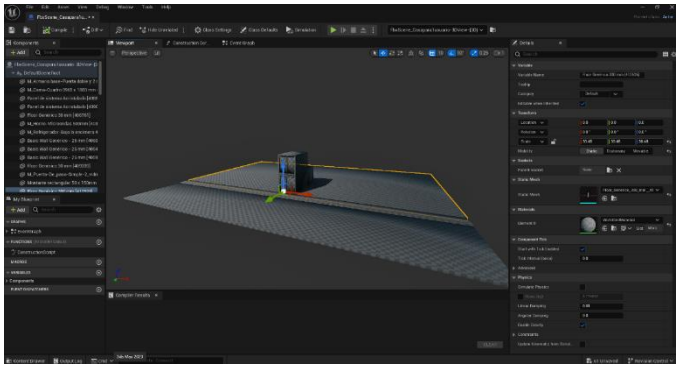


Fig. 8. UE importing (we can use .FBX)

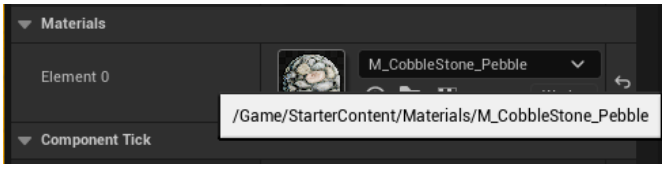


Fig. 9. Materials config

- Reviewing the imported model , if the model is complete and maintained its integrity in the import/export process .

- Test the scene , by running the project to ensure the functions are correct and working fine and the model appears as expected .

Fig. 10. Materials config 2

3.3.3. *Setting up first person perspective*

1) Add a first-person character:

- in UE go to content browser, navigate to add new button then select blueprint class.

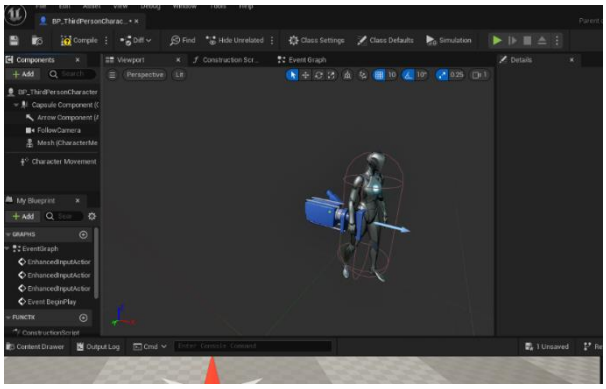


Fig. 11. Setting FPP 2

- choose (Character) as the parent class and name it ,after that we open the created blueprint and adding a (Camera component) to it , to be as our viewpoint.

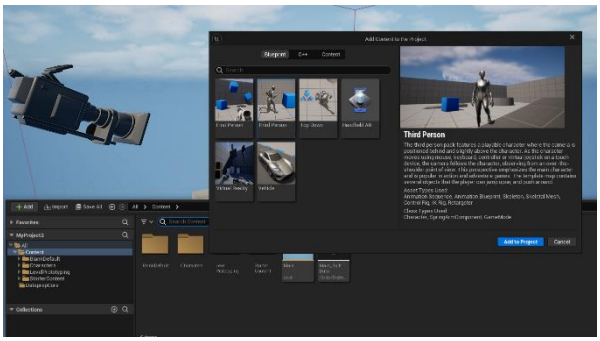


Fig. 12. Adding FPP to the project

2) Camera settings:

- adjusting the position of the camera, eye level, filed of view (FOV) and the aspect ratio.

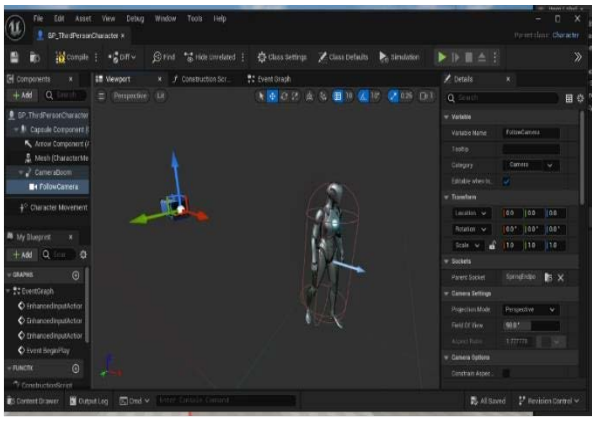


Fig. 13. Camera settings

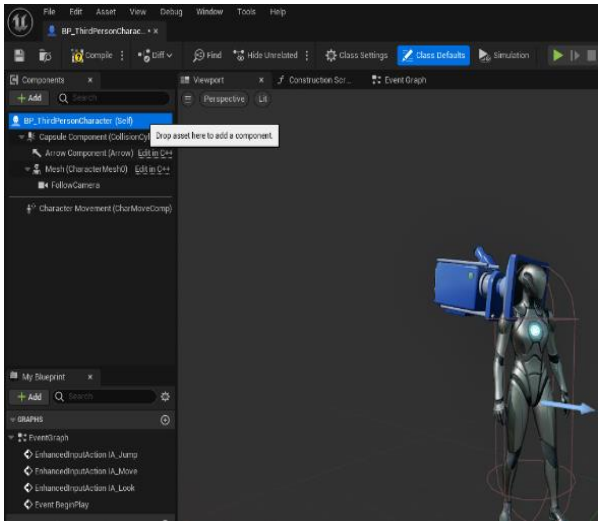


Fig. 14. Camera settings 2

3) Input control:

- Define the input mappings for movement, forward, backward ,left ,right. And controls (mouse or gamepad).

4) Movement logic:

- In the character blueprint, implement logic for movement and looking around using the input mapping we defined

- Use the (Add movement input) and (Add controller Yaw/pitch input) nodes to handle the character movement and camera rotation.

5) Setting the game mode:

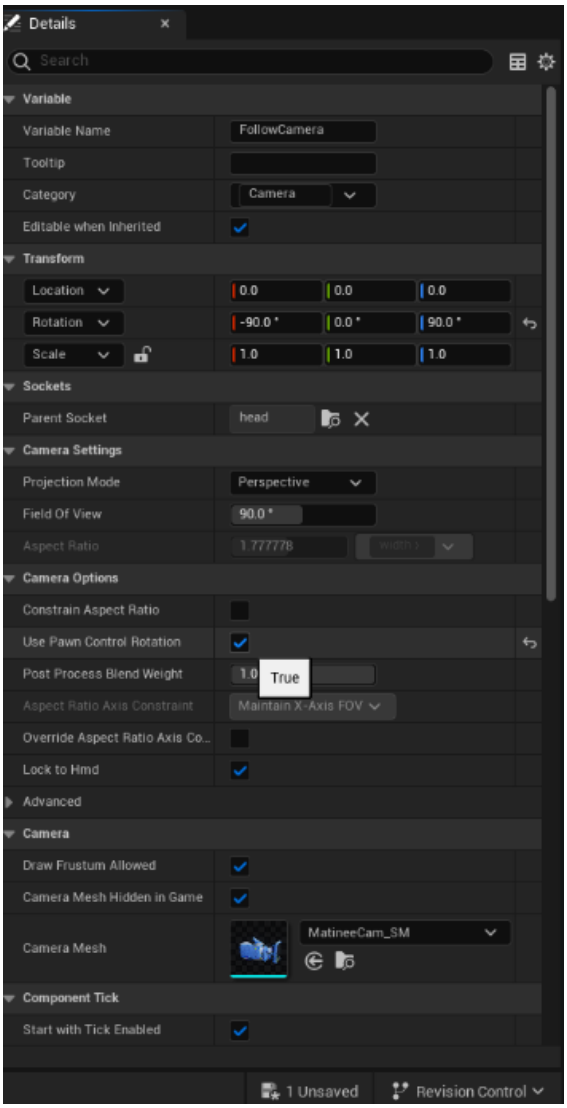


Fig. 15. Camera settings 3

- From Edit --Project settings-- Maps & Modes

-set the character as the default pawn in the game mode settings.

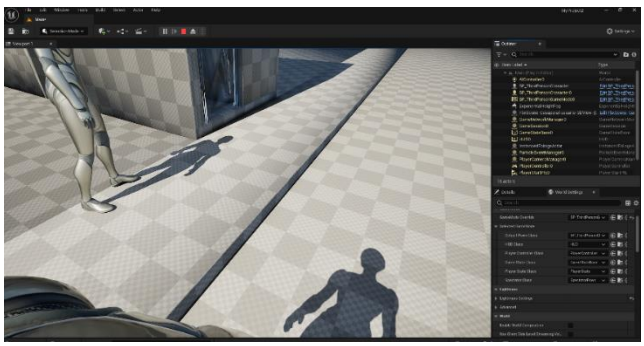


Fig. 16. Game mode selection

3.3.4. *Setting up VR*

1) Enable VR plugins:

- From Edit – Plugins and enable the required VR plugins (Steam VR), depending on the VR hardware.

2) Creating VR pawn:

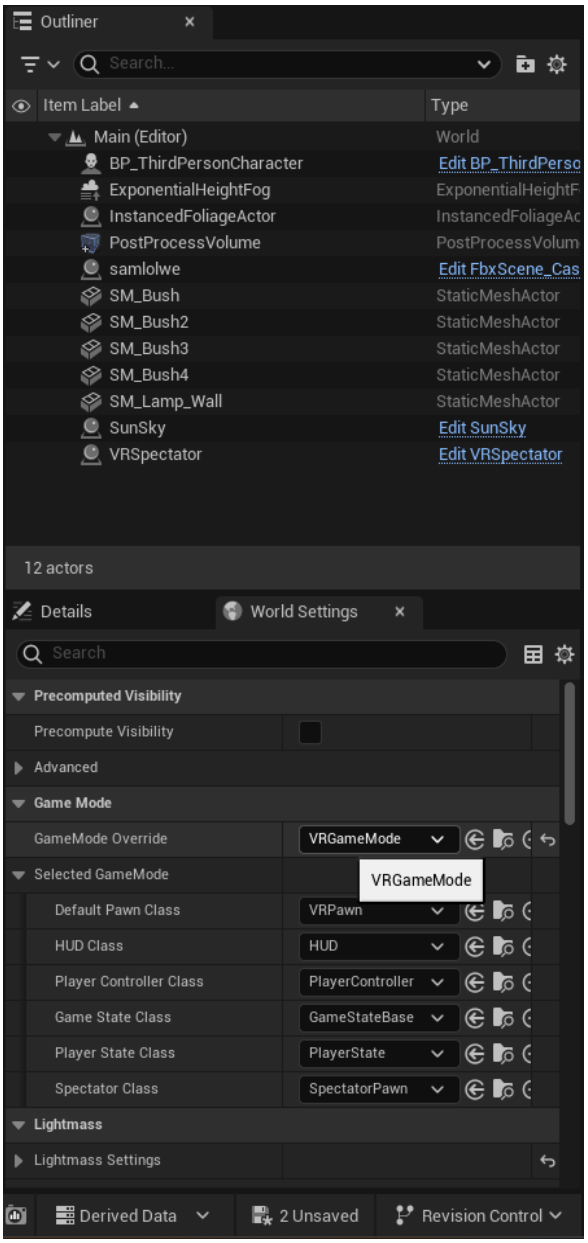


Fig. 17. VR mode selection

- Creating new blueprint class based on (Character)

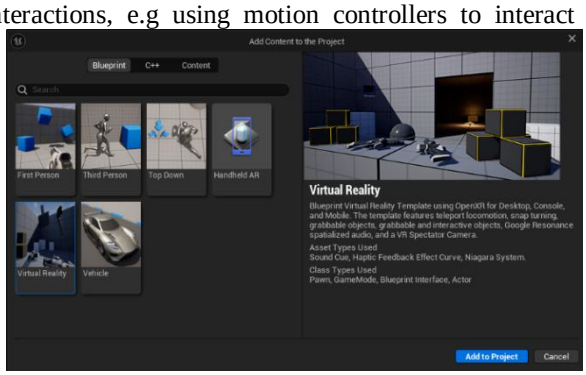
-Adding components for VR motion controllers (Motioncontroller components) and a camera

3) VR input:

- Set up input mapping for VR controls (grabbing, teleporting), same as first-person character.

4) Implement VR logic:

- In VR pawn blueprint, implement logic for VR interactions, e.g using motion controllers to interact with



objects in the environment.

5) Set the VR pawn as fault:

- Game mode settings, set as the default pawn class

Fig. 18. Setting VR

6) Testing

- Connect your VR headset and run the project to test the (first-person perspective) FPP and VR functions.

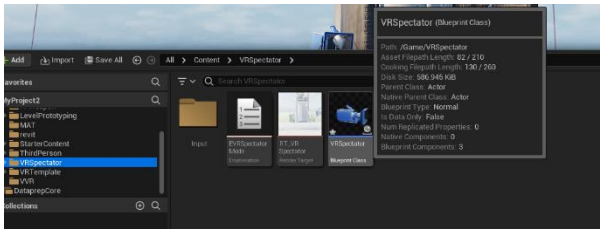


Fig. 19. adding spectator camera to test the VR environment

4. Results and Discussion

4.1. Prototype collection/Analysis

With the previous process, and learning from "Dwyer Architectural" presentations, we can present to the local workshop with a sample project completed using the same tools, the only cost of which will be the training and VR headsets, since the UE and the plugins are free. We can temporarily deliver the idea from a first-person perspective in case the VR headsets are not available.

Table 2. overview of some affordable VR headsets

VR Headset	Price	Description
Meta Quest 2	$299	A popular standalone headset offering great value for gaming and experiences.
Pico 4	$349	A versatile standalone headset with a strong library of games and applications.
Oculus Go	$199	An entry-level standalone headset ideal for casual VR experiences.
Samsung Odyssey+	$299	A tethered headset known for its high-quality visuals and comfort.
PlayStation VR	$199	A budget-friendly option for PlayStation users, providing access to a variety of games.

"The headsets as on amazon.com "

The first tangible change will be in the way the client is introduced to the building and how he can interact and develop a new feeling towards this space, the results will be a

motive for the teams to finish the projects with BIM and present it in this style, in the end the client cares more about the finished product, and the team focus on the quality achievements within the minimum modifications and conflicts in the project.

4.2. Effect on BIM maturity

- The scale of BIM maturity includes levels of collaboration, standardization, and the degree of integration of BIM in the project lifecycle.
- Collaboration: providing common, immersive platform for visualizing BIM models.
- Standardization: encourage the development and adoption of BIM process, as it is the key indicator for BIM maturity.
- Integration in project lifecycle: from design to construction and maintenance.
- Training: VR serves as a powerful tool for education and training to build a skilled workforce proficient in BIM
- Time frame for maturity: based on several factors, current level of BIM adoption, investment in technology, policy and regulations, industry collaboration.

The end value is substantial, affecting not just the efficiency and quality of the projects but potentially contributing to boarder economic growth and sustainability with a unique and fresh experience.

4.2.1. *Case studies data*

We can see that the integration of BIM and VR not only enhances the design and construction phases but also improves communication among stakeholders. The immersive nature of VR reflects better understanding and feedback, leading to more controlled outcome, additionally the focus on sustainability and heritage preservation demonstrate the potential of these technologies to align modern architectural practices with environment and culture.

Table 3. Case studies key integration

Project	Key Integration of VR with BIM	Main Benefits
The Edge, Amsterdam	Comprehensive digital model; immersive exploration	Enhanced collaboration and improved design feedback
V&A Museum	Complex structural modeling; immersive design reviews	Efficient design iterations and improved visitor engagement
Sagrada Familia	Streamlined restoration; quick design visualization	Enhanced understanding of architecture and efficient restoration

"The Edge, Amsterdam Showcasing an exemplary IoT building, Jalia A , Bakker R, Ramage M"

"Rafal Wojciechowski, Krzysztof Walczak, Martin White, and Wojciech Cellary. 2004. Building Virtual and Augmented Reality Museum exhibitions. In Proceedings of the ninth international conference on 3D Web technology (Web3D '04). Association for Computing Machinery, New York, NY, USA, 135–144.

"VR-assisted Architectural Design in a Heritage Site:the Sagrada Família Case Study Carlos Andujar, Pere Brunet, Jerónimo Buxareu, Joan Fons, Narcís Laguarda, Jordi Pascual, Nuria Pelechano"

Moreover, the impact of interior design emerges as a core factor in these projects, through enhancing user experience, ensuring the spaces are not only functional but also aesthetically pleasing and reflects the culture context.

In the V&A museum, for instance, the interior design elements were crucial to create engaging visitor experience, while in Sydney opera house project, the careful consideration of interior spaces contributed to preserve the building architectural integrity.

Table 4. Case studies key integration

Aspect of VR Implementation	Description
Immersive Design Review	Stakeholders used VR headsets to explore the digital model of the Opera House, experiencing the space as if it were finished. This facilitated better understanding and feedback on design elements.
Public Engagement and Education	VR was utilized to create virtual tours, allowing visitors to explore the building's history and architecture interactively, enhancing their appreciation of its cultural significance.
Training and Safety Simulations	VR simulations were employed for training construction workers and staff, allowing them to practice construction processes and safety scenarios in a risk-free environment.
Enhanced Collaboration	The use of VR allowed for real-time collaboration among architects and stakeholders, improving communication and decision-making throughout the renovation process.

"Cardellicchio L, Stracchi P, Globa A, Digital heritage construction: Testing the heritage value of construction documentation and building processes through Virtual Reality". These experiences points to the necessity of integrating advanced technology with strong interior design principles to create innovative, efficient and engaging environment for the client and the working teams .

5. Conclusion

The integration of VR with BIM represents a significant advancement in the fields of architecture and construction, offering huge potential for design visualization, collaboration

and project management. This thesis explored various aspects of VR-BIM integration, from the use of practical tools to facilitate this integration to the analysis of real-world case studies and future trends, more important is the result that we can achieve with dedicating the minimum resources.

key conclusions

1- The importance of interior design: the case studies showed that interior design played a pivotal role in enhancing user experience and pointed out the necessity of merging new technologies with a strong design principle, creating an optimum environment.

2- Economic and sustainable growth: by offering the clients this unique experience that aligns with modern architectural practice and introducing to the local market a new investment ideas.

3- BIM maturity: enhancing the crucial aspects of BIM maturity (e.g. collaboration) via VR and new visualization style, promoting the adoption of BIM and its applications.

Future work and Recommendations

Seeking advanced integration we have to focus on the following:

1- Investment in research and development: allocate resources to develop plugins and tools to facilitate the export and import processes between various software platforms

2- Training programs: educate the stockholders on the effective use of VR, focusing on technical skills and practices for collaboration in a VR environment

3- User-centered design: to improve user experience and reduce the learning stages for new users

4- Cost/value: explore and develop more affordable integration solutions to make this technology accessible to smaller firms with limited budgets .

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