

AUGMENTED REALITY FOR MODULAR CONSTRUCTION: A BIM DRIVEN FACTORY TO SITE WORKFLOW

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Abstract

The research presents ARsembly, an open source framework that bridges Building Information Modeling (BIM) and Augmented Reality (AR) within the Architecture, Engineering, Construction, and Operations (AECO) sector. The study addresses a persistent gap between traditional BIM AR proposals and their practical implementation in real-world workflows. Through the development of two interlinked frameworks, BIM AR integration and User Interface (UI), the work demonstrates a feasible, replicable approach for interactive BIM visualization and decision support in AR environments.

The BIM AR framework tackles key technical challenges such as model preparation, file transformation, runtime rendering, and device optimization, establishing a GLTF-based runtime pipeline compatible with free and open source tools. In parallel, the UI framework defines a modular structure that separates general functionality from AR-specific interaction, focusing on usability, cognitive clarity, and multidisciplinary adaptability. Together, these frameworks converge in ARsembly, a prototype developed in Unity with C#, Docker, and Python scripting to enable real-time BIM model visualization, metadata management, and AR-based interaction.

Results validate the feasibility of the proposed system through iterative testing, benchmarking, and partial implementation. The research concludes that BIM AR integration must be both technically grounded and user-centered, with flexibility and accessibility as key enablers of adoption in the AECO industry. ARsembly thus contributes a scalable model for open, interoperable, and human centric digital workflows supporting the ongoing transformation of construction processes toward smarter and data-driven environments.

1. Introduction

The AECO industry is facing a paradigm and digital metamorphosis from traditional to virtual, digital and innovative methodologies, such as BIM, AR, VR and others [9]. The aim of this transformation is to create greener, safer, efficient, creative and time-sensitive spaces through the life cycle of construction projects. While considering cultural changes in the way professionals interact, design, visualize, plan and collaborate.

The role of AR in this industry switch has evolved from isolated experimental initiatives to structured projects, capable of handling real life scenarios. However, despite its potential to merge digital content and physical environments, AR implementation in modular construction remains limited, affecting project accuracy, coordination, and efficiency. The proposed ARsembly addresses this gap by integrating BIM and AR with a realistic and replicable focus for the assembly of prefabricated elements.

The integration is through a BIM AR software, supported by a UI and a mobile AR frameworks. Enabling instant interaction of BIM models into an AR interface built with Unity Engine (C# scripting), Python scripting (GLTF conversion and metadata) and runtime API communication (Docker and containers). The application targets Android devices following four AR integration phases: initial decisions, format settings, metadata settings and AR placement.

The development process was supported by wireframes, storyboards, virtual prototyping, and iterative architecture definitions (Architecture α and β), enabling continuous usability evaluation and technical refinement. Methodologically, the study adopts an iterative and qualitative approach, combining technical development with design thinking principles. The research is structured as follows: 1) theoretical and practical review, 2) BIM AR framework, 3) UI framework, 4) frameworks implementation, and 5) results and conclusions.

2. Theoretical and practical review

Three primary research lines were identified during the literature review. The first concerns AR applications in construction, the second addresses the integration of BIM and AR, and the third focuses on the use of game engines as a medium for AR implementation.

AR is defined as the integration of virtual content into the real world to enhance user perception and understanding of spatial and graphic information [2]. In construction, AR supports real-time progress tracking and 3D/4D visualization [14], facilitates defect identification and coordination, and contributes to safety management and productivity monitoring [3;8]. However, limitations such as hardware demand, accuracy constraints, implementation costs, and workforce adaptability persist [14].

Additionally, AR has demonstrated potential to reduce cognitive load and physical errors during assembly processes by providing contextual and real-time guidance [7; 16]. Compared to VR and MR, AR remains the most practical and versatile technology for on-site visualization and workforce guidance in AECO contexts [17].

Furthermore, the second research line refers to the BIM and AR integration, where implementation of AR in BIM methodology offers a binocular or oculomotor experience (two or more visual inputs), improving the understanding of spatial environments [18]. Nevertheless, challenges remain due to limited training, lack of standardized guidelines, and interoperability constraints.

The third research line highlights the use of game engines for AR implementation. Gaming environments have been identified as effective platforms for learning complex tasks and simulating construction processes [1]. Two primary workflows to transfer BIM data into game engines are commonly used: 1) direct export to formats such as OBJ, FBX, or IFC, and 2) pre-rendering pipelines to preserve metadata [18]. Managing data complexity through Level of Information Need (LOIN) and Level of Geometric Granularity (LGG) is critical to reduce data loss and optimize performance.

Despite optimization efforts, BIM and AR workflows still face challenges related to metadata preservation and interoperability. While IFC is recommended for maintaining semantic data, most game engines lack native support, relying instead on intermediate formats such as FBX or OBJ [13]. Educational initiatives such as the ELBIGMAC project demonstrate how Unity and Unreal can support immersive BIM learning environments [15].

3. Augmented Reality framework

Prior to the definition of the AR framework for ARsembly, a benchmark study was conducted across eight game engines: A-Frame, Babylon, Cryengine, Godot, PlayCanvas, Unity, Unreal and Wonderland. The platforms were analyzed based on: development focus (web or mobile apps), device compatibility (mobiles, PC or HMD), BIM file format integration (interoperability with BIM formats) and operating system (Windows, iOS or Linux).

Unity and Unreal emerged as the most suitable platforms, with Unity selected due to its accessibility, learnability, extensive documentation, and availability of open source resources [6]. For runtime BIM integration, the GLTF format was selected for its balance between geometric accuracy, metadata handling, and lightweight performance, particularly in mobile AR environments where FBX runtime loading requires paid solutions [4].

The proposed AR framework (Figure 1) structures the integration into four stages: initial decisions (engine and platform), format setting (favoring GLTF for runtime), metadata setting (use of GLTF extras), and AR placement. The framework supports both offline and runtime scenarios and prioritizes plane detection and AR placement to mitigate issues related to marker instability and environmental sensitivity.

4. User Interface framework

This section defines the UI framework for ARsembly, based on Franklin Hernández Castro's twelve-phase methodology for software development [10]. The framework has been adapted to address Extended Reality (XR) contexts by creating a division of the interface into two parallel streams: General UI and BIM AR UI, beginning at Architecture α (phase four) (Figure 2).

The General UI handles standard functions such as menus, settings, and project management, while the BIM AR UI specifically manages AR visualization, marker or plane detection, and interaction with BIM content. This division is necessary due to the ineffective test of traditional design techniques such as paper prototyping into immersive 3D experiences.

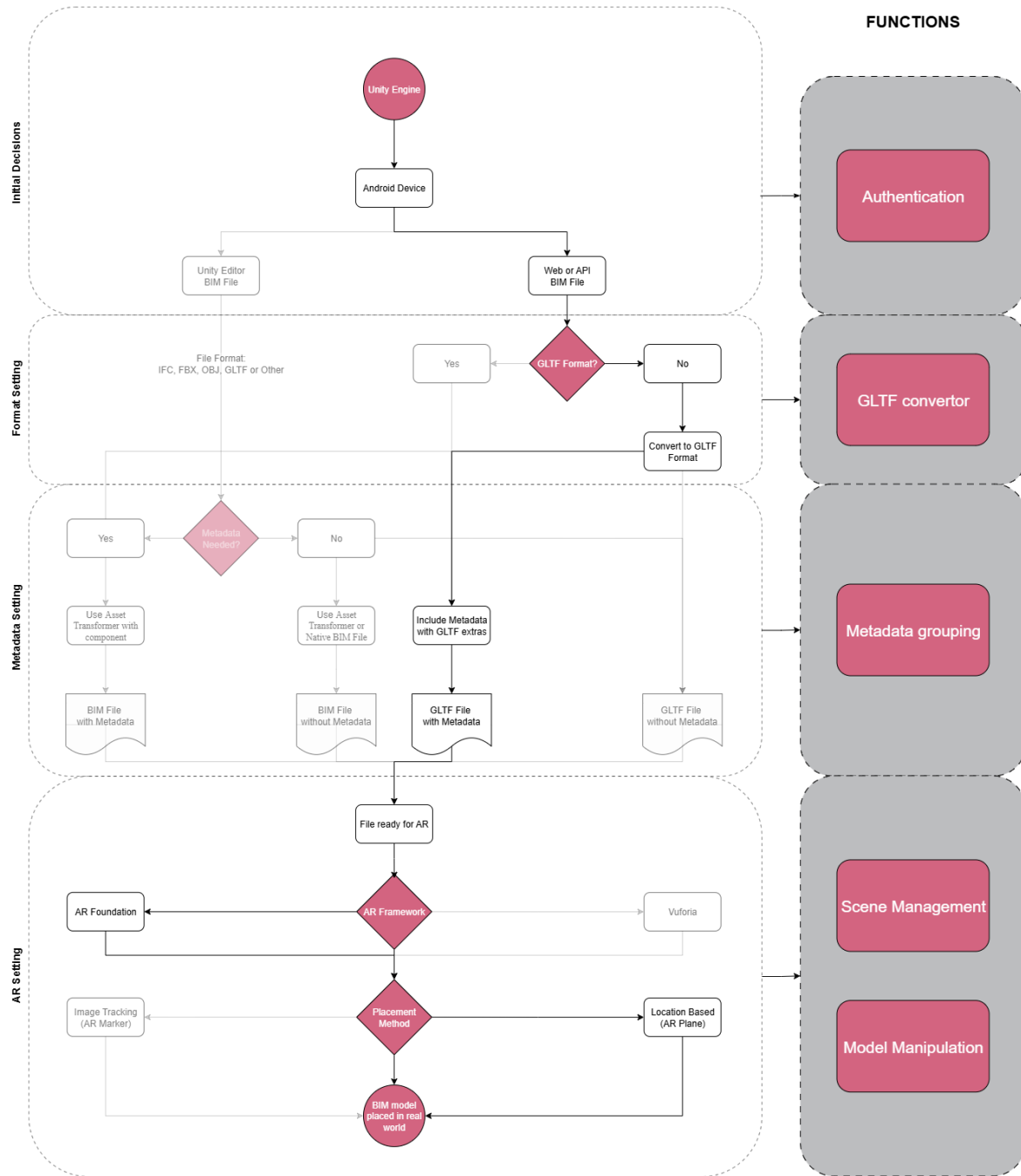


Figure 1: Proposed BIM AR Framework for Unity Engine with defined fectionalities

Virtual prototyping was introduced as a new and direct response to overcoming the limitations of traditional techniques. Enabling early testing on spatial interaction, reducing cognitive load and improving usability feedback [12]. In addition, it helps to gain familiarity with the AR and BIM technologies for unfamiliar workers, while keeping an open and communicative channel, minimizing the generational knowledge gap identified.

Usability test becomes the core feedback method for the BIM AR UI framework. Focusing on task performance, user verbalization, and observed behavior to identify issues that cause mental load, frustration or errors, and are repeated across stages [11].

A key finding is that BIM AR UI is dynamic and context dependent. Task complexity directly dictates the interface structure and AR effectiveness, reinforcing the need for modular and adaptable UI design [5].

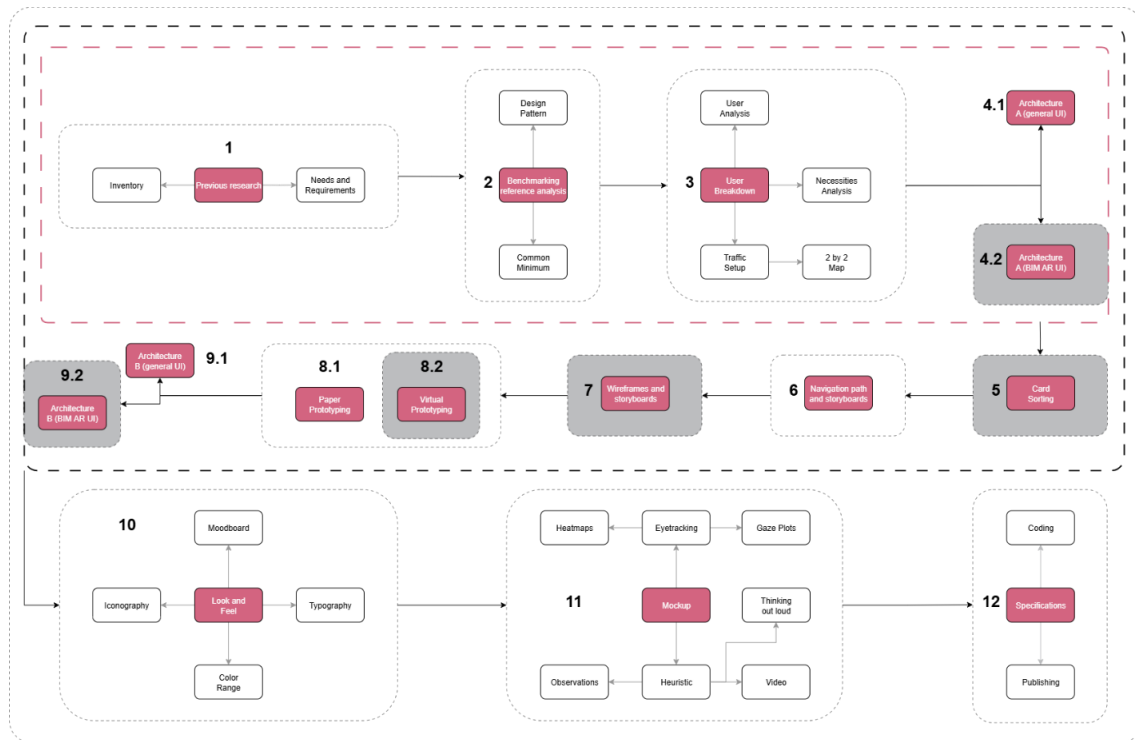


Figure 2: Proposed BIM AR Framework for Unity Engine

5. Frameworks implementation

The BIM AR framework has been fully implemented, while the UI framework was partially applied to its critical components. Benchmarking of eight AR tools (Cupix, Dalux, DarfDesign (Arki), Gamma AR, SmarTek (House Tour), Trimble Connect, VGIS and XYZ Reality) supports the definition of the Architecture α , identifying key design patterns such as sidebar controls, onboarding guidance, and clear AR workflows (Figure 3).

Additionally, the user analysis defined six archetypes: on-site worker, inspectors, project manager, client, logistics or inventory managers and BIM Coordinator/Manager. While mapping them 15 core application necessities emerged such as: 1) real scale visualization, 2) dynamic floorplan location, 3) categorization system, 4) tracking dashboard, 5) assembly and construction breakdown, 6) comments or specification sections, 7) connection setup, 8) quality takes off, 9) intuitive UI, 10) issues dashboard, 11) BIM integration, 12) accessibility and compatibility, 13) security control, 14) AR guidelines and 15) BIM guidelines. The analysis helps identify ARsembly's real needs, showing that AR and BIM guidelines should always be accessible, as these were the least well fulfilled aspects in the benchmarking analysis.

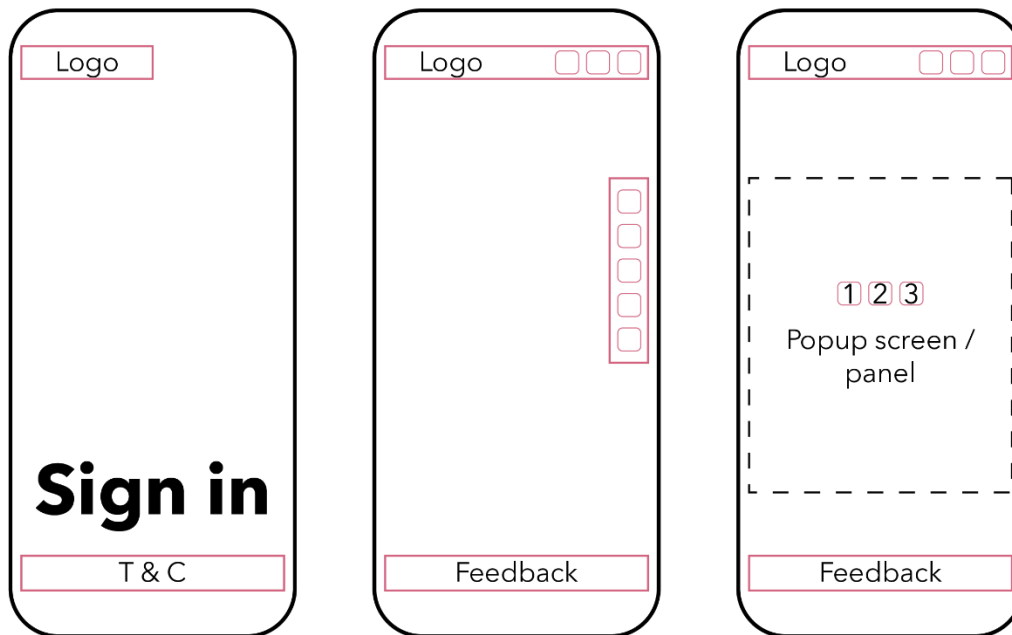


Figure 3: Summary of Identified Design Pattern

Technically, a Python-based pipeline using ifcOpenShell was developed to convert IFC and other BIM formats to GLTF, due to the lack of open source runtime support for these formats. BIM elements were grouped into the following eight IFC-based categories aligned with the buildingSMART IFC schema: 1) Walls: "IfcWall", "IfcWallStandardCase", 2) Floors or slab: "IfcSlab", "IfcFloor", 3) Structural elements: "IfcBeam", "IfcColumn", "IfcMember", "IfcPlate", "IfcReinforcingBar", 4) Mechanical elements: "IfcDistributionFlowElement", "IfcMechanicalFastener", 5) Electrical elements: "IfcElectricDistributionElement", "IfcElectricalElement", "IfcLamp", 6) Plumbing: "IfcFlowFitting", "IfcFlowSegment", "IfcSanitaryTerminal", 7) Furniture: "IfcFurniture" and 8) Finishing elements: "IfcCovering", "IfcSurfaceStyle".

During the conversion process, the metadata extracted from the IFC was only the one needed for ARsembly: 1) name, 2) type, 3) materials, 4) dimensions (width, height, and depth), 5) quantity, 6) specifications, and 7) color (only to be replaced for a single color on all the elements). As the rest of the metadata was not relevant for the visualization and classification of the elements, it was not processed or taken into consideration, meaning it was lost during the conversion. However, in case any other data is needed, it could be easily processed and incorporated during the conversion and metadata grouping stages.

The metadata grouped was embedded within the GLTF files using "extras." This GLTF pipeline enabled runtime model retrieval via an API and loading in Unity using the glTFast package.

Finally, virtual prototyping across four iterations refined the system (Figure 4), resolving UI overlaps and replacing marker-based tracking with plane detection placement. The final implementation demonstrates real-time BIM visualization, model manipulation, and assembly tracking within an integrated AR interface, validating the feasibility of the proposed frameworks.



Figure 4: Second Virtual Prototype

6. Results

The following images present the final implementation of the "ARsembly" application, showcasing the integrated UI and BIM AR frameworks in operation.

Figure 5 demonstrates the General UI, beginning with the authentication screen. Upon login, users access the project management dashboard, which reflects the updated "architecture β." Here, projects are categorized by type (Assembly/Installation) and status, with the option to archive completed work, addressing core necessities of scalability and task organization.

Figure 6 demonstrates the assembly tracking feature in use. The visual progress slider and element checkboxes allow users to toggle the visibility of completed items, directly applying the metadata grouping logic defined for the eight IFC categories. While showing the model manipulation panel. The sliders for rotation and scale adjustment highlight the C# coded functionality, enabling precise on-site control of the BIM model after placement via the AR plane method, confirming the successful separation from the general UI.

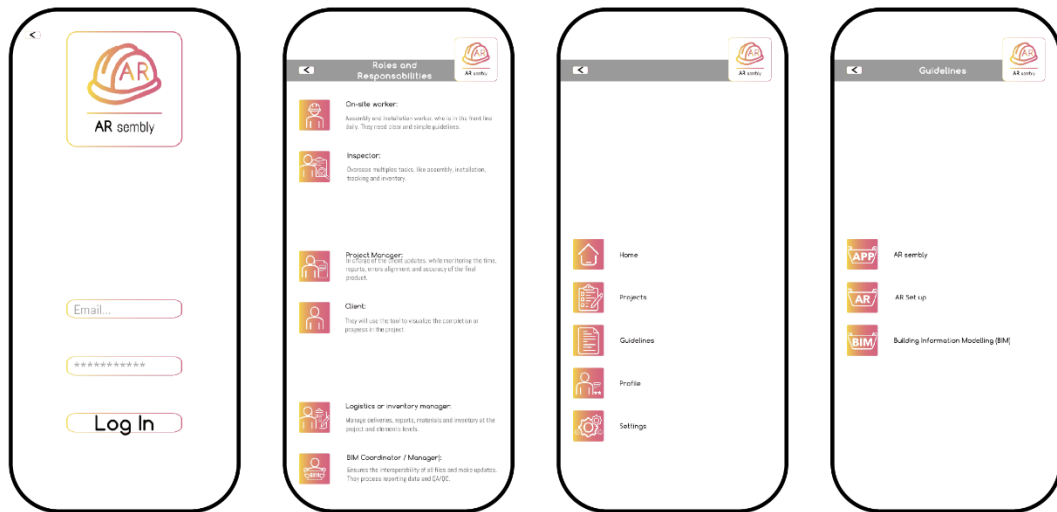


Figure 5: ARsembly Final General User Interface 1

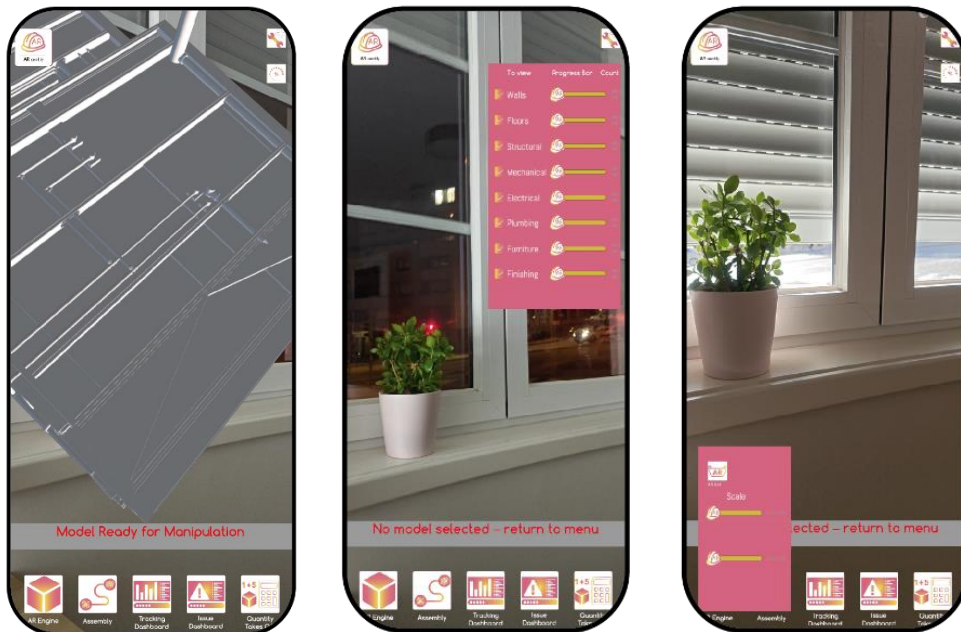


Figure 6: ARsembly Final BIM AR User Interface 2

7. Finals considerations and limitations

This research successfully developed a replicable, open source BIM AR system for the AECO sector. The research produced the "ARsembly" prototype, founded on two frameworks: a technical BIM AR framework establishing a GLTF-based runtime pipeline and a modular UI framework separating general and AR-specific interfaces. Iterative development, including

virtual prototyping, validated the approach and confirmed that effective BIM AR UI must dynamically adapt to task complexity.

The study had constraints, including the partial implementation of reporting features, a restriction on GLTF format for runtime loading, internal usability testing limited to Android and performance test such as latency, loading time, model size and other. The scope did not include integration with 4D scheduling, IDS, BCF or cross platform iOS/WebAR deployment. Some recommended next steps include implementing the full reporting module, expanding to iOS and WebAR platforms, conducting extensive field testing and validation with industry users, exploring advanced Natural User Interfaces (NUIs) like gesture control, and a final validation with a study case.

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