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Development of a BIM Object Partitioning System for 4D Simulation in Mixed Reality

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Abstract: This study introduces a novel system for the 4D simulation of Building Information Modeling (BIM) objects in mixed reality (MR) environments, addressing challenges of file format compatibility and data management. By developing a system that effectively partitions and manages BIM data, specifically utilizing the OBJ format, the study enables precise simulation of construction project changes over time. This advancement enhances visualization and decision-making in construction project planning and execution. The study highlights the integration of BIM and MR technologies, facilitating enhanced project management and operational workflows. Future work will focus on expanding compatibility with various BIM data formats and MR devices, and integrating AI-based data analysis for more accurate and efficient construction simulations.

Key words: Building Information Modeling, Mixed Reality, Data Partitioning, OBJ format, Construction 4D simulation

1. INTRODUCTION

Building Information Modeling (BIM) is an innovative design methodology that provides three-dimensional, object-based information throughout the entire lifecycle of a construction project, including design, construction, and maintenance. This methodology supports efficient decision-making among project participants by integrally managing and delivering vast amounts of data generated during the design processes [1]. While traditional two-dimensional CAD drawings have limitations in conveying spatial relationships and complexity adequately, the use of three-dimensional drawings through BIM overcomes these limitations, contributing to early design error detection and correction, minimizing delays, reducing costs, and improving quality [2-4].

Mixed Reality (MR) technology merges the real world with virtual objects to provide a new visual experience, allowing users to interact with virtual information in real-time [5]. In the construction industry, integrating BIM data into MR environments to enhance understanding of plans and reduce construction errors is a growing area of research [6-7]. These studies include attempts to realize 4D simulations through MR.

However, effectively visualizing BIM data in an MR environment faces constraints related to specific file formats. The OBJ file format, one of the open standard formats for storing 3D modeling data, features a text-based structure and is widely used across most 3D graphics software [8]. However, due to its simple text-based structure, the OBJ format has limitations in managing and visualizing complex BIM data effectively in an MR environment. Particularly, this format struggles to represent temporal changes in complex BIM object data and various interactions, making 4D simulation in an MR environment challenging. Moreover, the OBJ format's limited capability for detailed data processing, such as separating BIM objects, poses significant restrictions on accurately simulating changes at construction sites over time.

This study proposes a novel approach to the 4D simulation of BIM data in an MR environment. It aims to develop a system capable of efficiently partitioning and managing BIM data, particularly offering the ability to precisely simulate the chronological changes of construction projects. This will aid designers, constructors, and project managers in better understanding the site conditions and taking necessary actions based on the project's temporal progression. This study has developed a system that addresses issues stemming from file formats and enables effective 4D simulation of BIM data in MR. The scope of this study is limited to designing and developing a system that effectively integrates BIM and MR technologies to enable BIM object simulation at construction sites. The research procedure is as follows:

1. Conduct a literature review on trends in 4D simulation in MR environments and investigate existing file format conversion methods, specifically IFC and FBX.
2. Develop a customized module in Revit for partitioning and storing BIM drawings. This study names this system the "BIM Object Partitioning System (BOPS)."
3. Develop an MR application capable of simulating partitioned BIM objects (in OBJ file format) in an MR environment.
4. Test and validate the performance of the BOPS.

2. Literature review

Research in 4D simulation utilizing MR presents significant technological advancements for efficiently planning, constructing, and managing projects in the construction sector. MR integrates the features of Virtual Reality (VR) and Augmented Reality (AR), enabling interaction between real and virtual environments. Leveraging such technologies can enhance project visualization and collaboration, reduce errors, and increase safety and comprehension. Boton (2018) proposed a unique environment that supports constructability analysis meetings in the construction industry through VR-based collaborative BIM 4D simulation [9]. This study focuses on utilizing 4D-based constructability analysis more collaboratively. Wang et al. (2022) presented a method to enhance the efficiency of 4D simulations in construction environments by integrating BIM and AR technologies [10]. Their research aims to increase simulation efficiency by integrating the surrounding environment into the structural model. Bouron and Boton (2019) explored methods to automate the integration of 4D simulation in a VR environment, intuitively generating construction process simulations [11]. Hilfert and König (2015) introduced a method to create highly immersive VR environments in engineering and construction fields at low cost [12]. Their study enables users to naturally review virtual models using head-mounted devices like the Oculus Rift. Sampaio and Martins (2017) explored using VR technology to develop a visual simulation of bridge construction for educational purposes [13]. Their model supports education by visually simulating the bridge construction process and the use of necessary equipment on-site.

These research outcomes demonstrate that 4D simulation and MR technologies can play a vital role in the planning, construction, education, and collaboration processes of construction projects. The integration of MR technology and 4D simulation can enhance project comprehension, support decision-making, and facilitate collaboration, thereby improving the efficiency and safety of the construction industry.

MR environments face limitations in 4D simulation due to restrictions on compatible file formats and difficulties in smooth progression with large file sizes [14-15]. Kim et al. (2019) pointed out the need for large data transmission within limited bandwidth when delivering 3D data via head-mounted displays (HMDs) [16], such as HoloLens, leading to device performance issues and burdens due to large data transfers [17]. It was anticipated that developing a method to deliver 3D data to devices in smaller sizes could minimize these burdens. Na and Hong (2023) noted that while complex 3D mesh models

are necessary for realistically representing spatial objects like facilities, the limited performance of devices like mobile devices hampers smooth operation due to rendering performance limitations [18].

The International Foundation Classes (IFC) format is widely used for BIM collaboration and file sharing. However, IFC files pose file size issues when visualizing 3D models [19], and reviewing BIM modeling information within IFC files requires installing specific applications due to accessibility constraints related to certain operating systems [20]. Moreover, using IFC files in MR environments necessitates conversion to compatible formats due to Unity3D's inability to recognize IFC files directly, leading to research utilizing converted FBX for use in Unity3D [21]. However, converting IFC files to 3D models requires polygon reduction adjustments to decrease loading times due to excessive polygon generation [22]. Meanwhile, FBX format has compatibility issues with material recognition [23], as Unity3D does not support Autodesk's material library, leading to situations where geometry and scale remain intact, but material data is lost [24]. Thus, a process using the 3Ds MAX rendering program to convert material data is necessary to prevent this loss of material data [25].

The OBJ format, developed by Wavefront Technologies, is a text-based 3D file format. However, its text-based nature limits the ability to toggle visualization of objects on/off within the Unity3D environment. For 4D simulation, it is necessary to have time-specific visualization settings for objects, but OBJ files do not support this feature. This study aims to overcome the limitations of OBJ files and develop a system that facilitates smooth 4D simulation in MR environments.

3. System Development

3.1 System Design

Table 1 outlines the BOPS configuration, which is divided into three main modules: 1) The Schedule Input Module allows users to input scheduling information for BIM objects, including installation start and end dates. 2) The Objects Query & Export Module facilitates storing objects within a specified time range as OBJ and CSV files, enhancing data management efficiency. Developed as Revit add-ins using C# in Visual Studio through Revit's API, these modules integrate seamlessly within Autodesk Revit, streamlining the workflow for users. Lastly, the 4D Simulation Module, created as an application for MR devices, merges OBJ geometric data with scheduling details from CSV files to progressively render BIM objects. This cutting-edge module is engineered in Unity3D and is compatible with Microsoft HoloLens2, offering immersive visualization capabilities.

Table 1. System Components

Module	**Programed in**	**Operate in**	**Function**
Schedule Input Module	Visual studio	Revit	Add attributes to BIM objects
Objects Query & Export Module	Visual studio	Revit	Data partitioning and export
4D Simulation Module	Unity3D	HoloLens2	4D Simulation in mixed reality

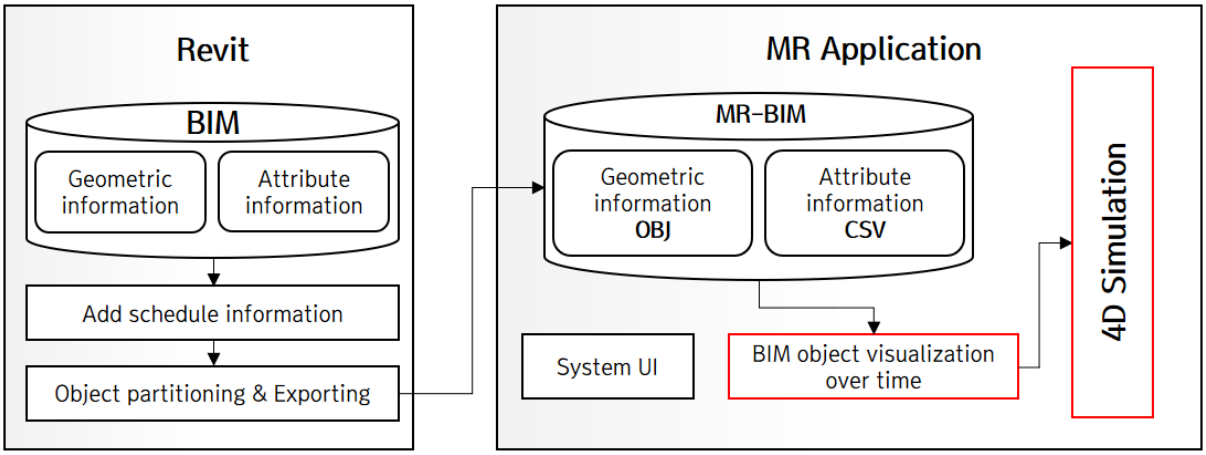


Figure 2. Data workflow

The study's data workflow, illustrated in Fig. 2, shows the process where users partition and export BIM objects into geometric data in OBJ format, accompanied by attribute data in CSV format. This attribute data covers essential details, including material specifications, construction sequencing, and project duration. A notable advancement is the storage of OBJ files not as a single, unified file for the entire project but as separate files for each individual object. This approach enhances object-specific visualization capabilities within Unity3D, allowing for more detailed and accurate simulations of the project.

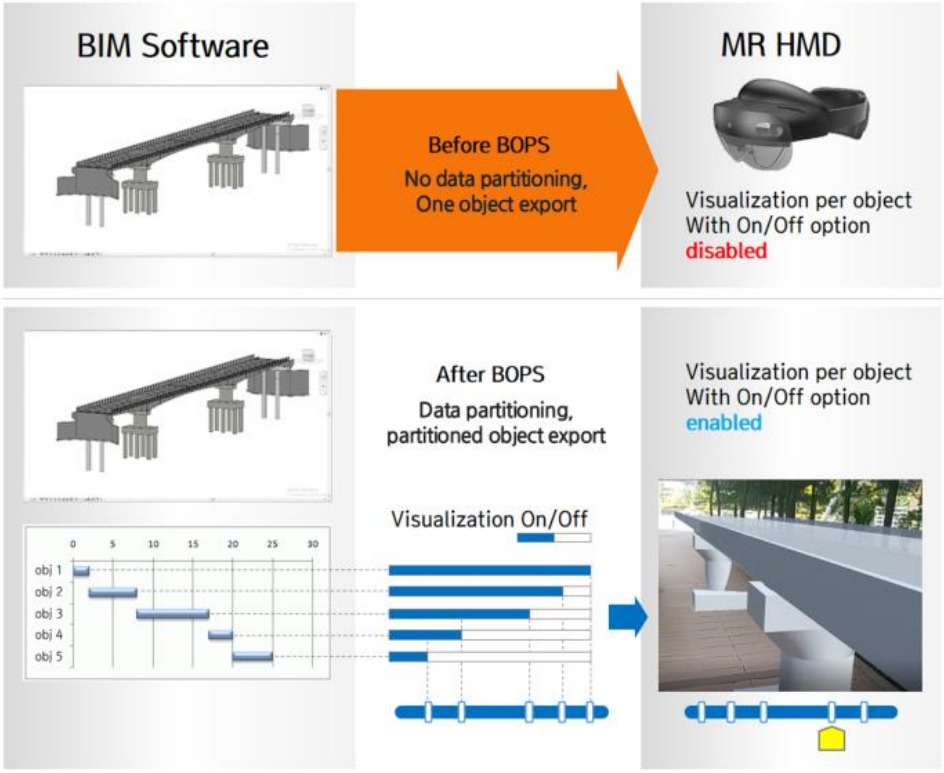


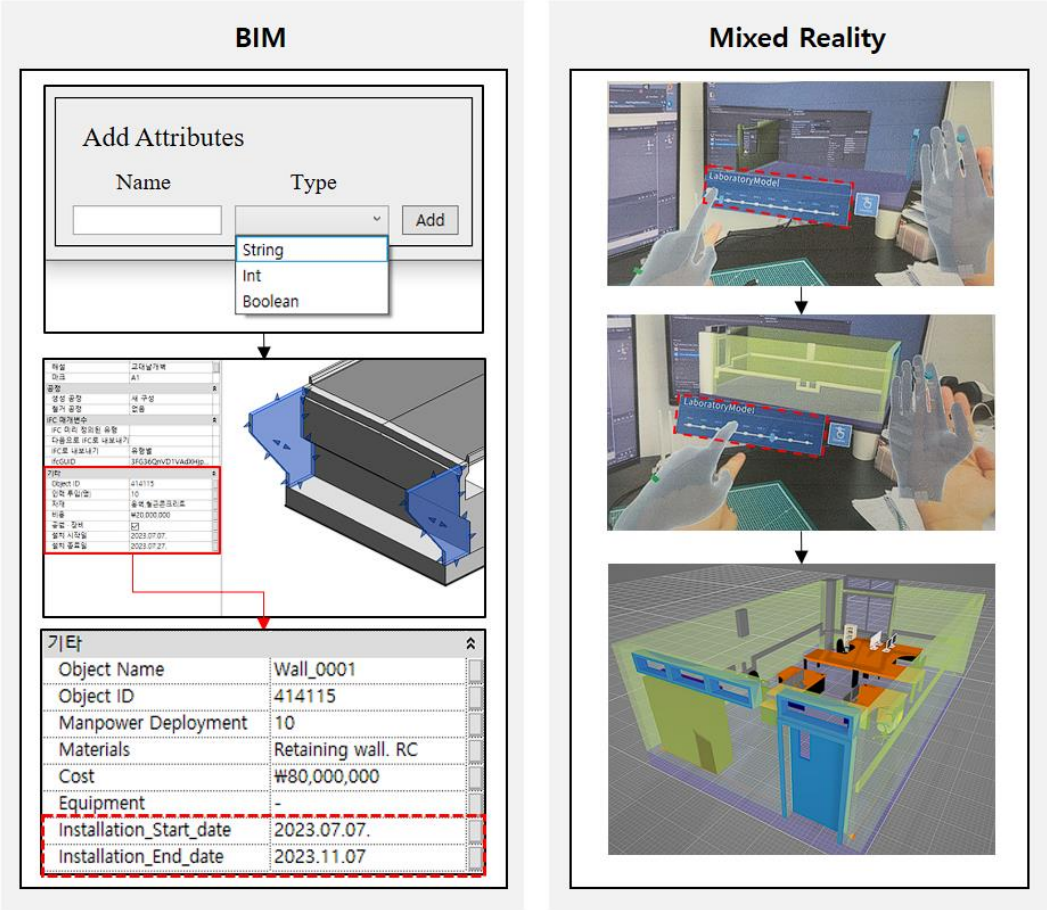
Figure 3. Concept of BIM objects partitioning

Typically, when exporting BIM drawings to OBJ format in Revit, the entire drawing is saved as one OBJ file. This method does not allow for object-specific separation, making time-dependent simulations in Unity3D challenging. However, the separated files for each object, generated through the BOPS, enable 4D simulations based on the schedule information each object contains (Fig. 3).

3.2 System Demonstration

The core functionality of the BOPS lies in its ability to efficiently partition BIM objects and accurately simulate the construction process as it evolves over time. Fig. 4 shows the process of using BOPS. Users can add schedule information directly to BIM objects using add-in features developed in Revit (Fig. 4(a)). For BIM objects already containing schedule information, they can be applied directly to the system without the need for schedule data input. This process allows users to select only the necessary objects for their project requirements and export them in the OBJ format, significantly simplifying the data preparation process for 4D simulation.

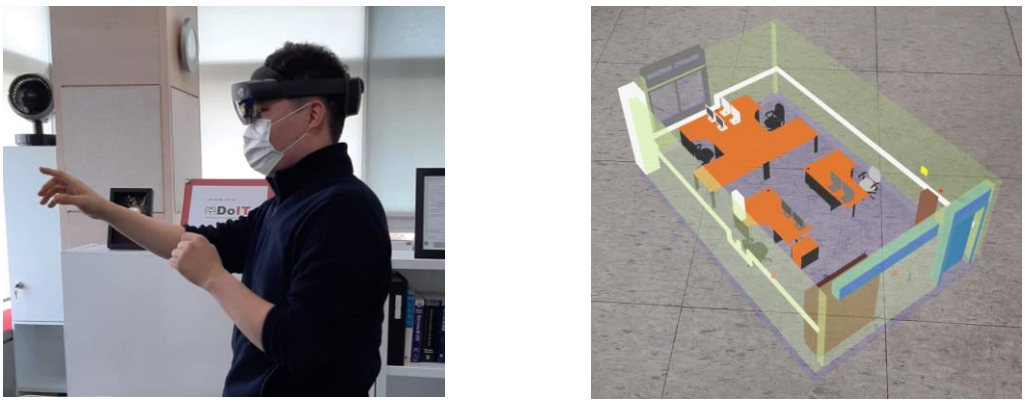
In the following step, users execute the 4D simulation within an MR environment using the OBJ files prepared in the previous step. During this process, users can manipulate a timeline slider to select a specific point of interest. Only the BIM objects corresponding to the selected time point are visualized, enabling users to precisely understand the construction situation at that moment (Fig. 4(b)). This capability greatly assists project managers and on-site workers in identifying and addressing potential issues during the construction process. Furthermore, 4D simulation via BOPs enhances the efficiency of overall project management by enabling real-time tracking of project progress and supporting decision-making based on this information.



(a) Adding Schedule Information (b) 4D Simulation in Mixed Reality

Figure 4. Process of using BOPS

To ascertain the efficacy of the BOPS in MR environments, a test was implemented, aimed at examining its capabilities in accurately partitioning BIM data and enabling refined 4D simulations (Fig. 5). The assessment contrasted the performance of the BOPS against traditional BIM visualization methods, showing a notable improvement in the quality of visualization and the interactivity in MR. Feedback from a diverse range of testing participants, including project managers and civil engineering students, emphasized the system's intuitive interface and seamless BIM data integration, significantly simplifying the visualization of complex construction sequences. Preliminary results underscored a notable improvement in stakeholders' comprehension and involvement in the construction process, suggesting the BOPS's vital role in elevating project planning and execution efficiency. Additionally, the system's adaptability was rigorously assessed across different project scales and complexities, affirming its potential for widespread application in the construction industry, thereby meeting its rigorous visualization and simulation demands.



(a) A user wearing an HMD (b) BIM in Mixed Reality

Figure 5. System demonstration

4. Discussion

The core contribution of this study is making 4D simulations of BIM objects in MR environments possible, overcoming previous limitations due to file format restrictions. This achievement marks a significant advancement by enabling real-time visualization and simulation of construction projects using BIM objects. The research developed a system for efficiently managing and partitioning BIM data in the OBJ format, offering a new methodology for precise and efficient simulation of construction project changes over time. The BOPS significantly reduces BIM data loading times in MR environments and enhances user interaction through optimized data processing techniques.

The industrial significance of BOPS lines in its potential to improve time and cost efficiency in construction project planning and execution stages. By facilitating real-time 4D simulation for decision support, the system enhances communication among project participants and minimizes errors, thereby opening possibilities for revolutionary improvements in project risk management within the construction industry.

The limitation of the current study is its optimization exclusively for OBJ format data, necessitating further research for compatibility with various BIM data formats. Additionally, the system's optimization for specific hardware environments indicates the need for further studies to ensure its general applicability across different MR devices. Future research directions include expanding compatibility with various BIM data formats and MR equipment, exploring the system's application in construction safety management and maintenance, and integration artificial intelligence (AI)-based data analysis techniques to enhance the accuracy and efficiency of construction project simulations and analyses.

5. Conclusion

The transition to BIM is bringing revolutionary changes across all sectors of the construction industry due to the limitless potential of BIM. There is a growing interest in utilizing BIM objects within MR environments. However, progress has been slow due to issues related to the large size of BIM data and file format compatibility. In response, this study developed a BIM object partitioning system for 4D simulation in MR environments. This system proposes a novel approach for efficiently segmenting and managing BIM objects, enabling precise simulations of construction project timelines. Importantly, it leverages data in the OBJ format to facilitate 4D simulations in MR environments, laying the technical groundwork for this capability.

The system developed in this study utilizes the OBJ file format to efficiently implement BIM data within MR environments, overcoming challenges associated with traditional formats like IFC or FBX. It establishes a foundation for accurately simulating temporal changes in construction projects. This technological advancement supports decision-making processes at all stages of construction projects, enhancing efficiency.

The significance of this study lies in its innovative approach to integrating BIM and MR technologies in the construction industry. The developed system demonstrates the potential to enhance visualization and management of construction projects, significantly improving time and cost efficiency. Moreover, this study lays the groundwork for future construction project management methods by presenting a new direction for the integration of 4D simulation and mixed reality in the field of construction engineering.

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