MR-based Immersive Co-Design of Housing for Climate Displacement

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Abstract –

The rapid change in global climatic conditions and the increasing number of severe climate events have urged the demand for rapid, installable, customized, and sustainable housing solutions for climate-affected and displaced populations. To address this concern, this study develops a modular housing system tailored for climate displacements that integrates prefabricated bio-panel construction with an immersive digital design and evaluation workflow. The proposed design approach is based on the Building Information Modelling (BIM) framework to enable the systematic parametric integration of architectural quality, structural coherence, environmental performance, and human-centered design criteria.

An example of a housing design deliverable is studied based on dry-assembled prefabricated bio-panel components to support rapid on-site installation, reduced construction time, and limited dependence on skilled labor. Prefabrication design logic allows individual units to operate independently or be assembled as a large housing compound, which will facilitate expandable displacement community developments across diverse climatic and geographical regions. The BIM design is integrated with the Low-Latency Mixed Reality Design Platform (LMRDP) through a customized Revit API–based workflow, enabling high-fidelity design visualization to engage users. This integration enables seamless data transfer to an almost real-time MR application deployed to an MR headset. Based on the example demonstration, this study showcases a pathway to the combined potential of modular construction, BIM, and MR to enhance early-stage design evaluation, spatial usability assessment, and user engagement to support sustainable housing solutions for climate-affected displaced populations.

Keywords – **Climate displacement; Modular housing design; Building Information Modeling (BIM); Mixed Reality (MR); WebSocket**

1 Introduction

Climate change has increased the number of people to lose their homes due to floods, fires, droughts, and other natural disasters. Every year, millions of people are forced to move and become climate refugees. Many of them need safe and comfortable housing that can be quickly built and used for different lengths of time. Traditional emergency shelters are often constructed in a hurry, using materials that are not environmentally friendly and do not provide adequate living comfort.

Modern construction methods allow for the design of modular prefabricated houses that can be manufactured in a factory, easily transported, and quickly assembled on site. These systems allow buildings to be reused or relocated as needed, reducing waste and promoting sustainable construction. Previous studies show that modular and off-site construction supply chains can save time, lower costs, and improve building quality [1][2] in post-disaster situations.

This study is designed based on the climate refugees' community needs for temporary homes that are easy to build, move, energy efficient, and comfortable to live in. The design uses EcoCocon straw panels as the main material for walls and roofs. These panels provide good thermal insulation, allow the building to "breathe," and store carbon throughout their lifetime [3]. The use of natural materials helps to create healthy indoor conditions while reducing the environmental impact of construction. Several types of modular units, including small and medium-sized residential buildings, multi-room family modules, office and technical units, as well as shared spaces such as playgrounds, are proposed. Each module can be combined with others or used separately, depending on the number of residents and the specific location.

Thus, the study presents proof of concept design and system development efforts that integrate climate-responsive design, modular construction, and a mixed reality (MR)-based digital toolkit. Overall, the study indicates how modular construction and biomaterials can help create climate-resilient homes that are fast to build, easy to transport, and pleasant to live in. For this purpose, a digital toolkit using MR and WebSocket is developed to enhance the visualization experience. The BIM model of the housing design, with local climate data (temperature, wind, etc.) adapted to it and available cost-effective materials, is integrated into an MR environment through a self-developed low-latency MR design platform using Revit API, WebSocket protocol, and the Microsoft MRTK-3. By bridging the gap between static architectural data and immersive environments, the toolkit provides a platform for stakeholders to visualize, iterate, and optimize climate refugee housing solutions in real-time.

2 Literature review

The literature and market survey indicate that cost-effective material selection for climate refugee housing is closely linked to prefabrication, dry assembly, and lifecycle performance. Bio-based prefabricated panels, engineered timber systems, and Structural Insulated Panels (SIP) technologies are repeatedly highlighted as materials that reduce construction time, labor intensity, and waste through factory-controlled production [4][5][6]. Studies emphasize that lower embodied carbon materials, such as straw-based panels and timber products, contribute to long-term environmental savings while supporting rapid deployment [4][7]. Industrial panel systems benefit from standardization, predictable performance, and reduced on-site errors, further improving cost efficiency [6][8]. The literature emphasizes that cost effectiveness must be evaluated across the full life cycle, including transport, assembly, reuse, and potential disassembly [9][10].

Comparative analysis identifies three main material groups relevant to accelerated housing construction: bio-based prefabricated panels, engineered wood and CLT systems, and SIP or sandwich panel technologies [4][5][6]. Bio-based panels, such as straw- and hemp-based systems, prioritize low embodied carbon, carbon sequestration, and healthy indoor microclimates while remaining suitable for rapid dry assembly [4][11]. Engineered timber and CLT panels provide higher structural capacity, scalable panel dimensions, and predictable mechanical performance, enabling applications from single units to multi-story prefabrication [5][7]. SIP and sandwich panel systems focus on speed, airtightness, and high thermal resistance, offering reduced assembly time compared to conventional masonry construction [6][8].

The reviewed literature highlights that panelized and modular construction systems are well-suited to BIM-based housing design due to standardized geometries, defined tolerances, and repeatable connection logic [5][6]. Manufacturer documentation for CLT, SIP, and proprietary panel systems provides technical data that can be directly integrated into BIM workflows, supporting coordination between structure, enclosure, and building services [5][10]. Prefabrication supported by BIM improves logistics planning, panel sequencing, and quality control, reducing construction errors and material waste [7]. Standardized fastening systems, membranes, and connection components further support digital coordination and reassembly potential [7][12] [13].

The literature consistently emphasizes that temporary housing must focus on human comfort, health, and adaptability alongside technical performance. Bio-based panels are known for their positive impact on indoor air quality and hygrothermal behavior, supporting healthy indoor environments for displaced populations [4][11]. High thermal resistance, airtightness, and moisture control are identified as critical factors for maintaining comfort across different climates [6][8]. Modular panel systems allow flexible layouts and scalable unit combinations, supporting various household sizes and shared community spaces [7]. Material selection is therefore shown to influence not only environmental performance and reusability but also occupants' sense of safety, comfort, and acceptance of temporary housing solutions [9][10].

The integration of BIM and MR represents a shift from traditional, asynchronous file-based exchanges toward synchronous, model-based collaborative environments [14]. BIM parametric designs are useful for managing the prefabrication supply chains and mass customization of houses [15]. MR distinguishes itself from other immersive technologies by overlaying virtual models onto physical contexts to facilitate real-time decision-making and on-site coordination [16][17]. Current literature suggests that integrating immersive technologies with parametric BIM models allows for the simulation of complex variables, such as energy performance and material impacts, within a shared digital-physical space [18][19].

To overcome the interoperability limitations of traditional formats like IFC and gbXML, recent research emphasizes the necessity of real-time, bidirectional protocols [19]. By utilizing low-latency frameworks such as WebSocket alongside specialized toolkits like Microsoft MRTK-3, designers can establish an open-source toolkit. This integration ensures data continuity and enables multiple users to visualize, edit, and validate housing designs simultaneously, ultimately reducing material wastage and ensuring that climate-responsive shelters can be optimized based on their specific geographic and economic constraints [20][21][22].

Conventional web communication protocols, such as HTTP and TCP/IP, are reliable but limited for real-time collaboration between BIM and MR [23]. They rely on request-response models that require established and closed connections, which causes non-negligible latency [24]. In HTTP, every client's request starts a new connection. It receives the server response after transmitting header data, creating significant delays for real-time connections required by multi-BIM collaboration [25][26]. As for TCP/IP, it requires frequent handshakes and acknowledgments, making it inefficient in terms of low-latency synchronization scenarios [24].

On the other hand, the WebSocket protocol solves these problems by providing a persistent, bi-directional channel over a single TCP connection, allowing clients and servers to exchange messages and data simultaneously without repeatedly building connections [27]. Once the initial handshake occurs, both client and server can push updates instantly, which reduces latency and resource burden. The research conducted by Łasocha and Badurowicz shows that when transmitting more than 100 copies of data using the WebSocket protocol (compared to HTTP), performance can be increased by several hundred percent [24]. While latency tests run by Pandey and Gill present that under high concurrency (5,000 users), the WebSocket application maintained an average latency of 30ms, compared to an average of 120ms for the HTTP long-polling application [28].

3 BIM-based modular housing design

3.1 Conceptual design of the house in BIM

The proposed system of temporary modular housing for climate refugees is grounded in the principles of mobility, modularity, and sustainability. Its primary aim is to deliver dignified, energy-efficient housing that can be deployed quickly and adaptable in different climatic conditions and social settings.

Each unit, Residential Single, Residential Double, Residential Multi-room, Office, and technical modules, is designed as part of a flexible and adaptable assembly system. Depending on the emergency situation, modules may function as standalone units or be combined to form compact settlements. Residential units are intended for two- and four-person households, while larger multi-room and dormitory configurations allow for shared facilities such as communal kitchens and sanitary cores. The detailed floor layout of the Residential Double module is shown in Figure 1, while Figure 2 presents a three-dimensional schematic view of the module, illustrating its spatial organization and structural logic. This modular logic supports the development of scalable settlements that encourage social interaction and community cohesion.

The housing modules are conceived as self-contained units that can also be interconnected through shared energy and water infrastructure where appropriate. This approach allows communities to function semi-autonomously while maintaining resilience in situations where existing infrastructure may be disrupted by natural disasters.

The modular system enables flexible reconfiguration across different terrains, climates, and settlement scales, with units operating independently or forming larger housing clusters. To accommodate varied site conditions, the housing units are designed to be installed on pile foundations, which allow construction on uneven or challenging terrain with minimal ground intervention. Lightweight construction and dry-assembly methods allow efficient installation, dismantling, and relocation. This approach corresponds with research on modular and off-site construction, which highlights improvements in response speed, cost efficiency, and sustainability in post-disaster housing [1].

3.2 Design philosophy and architectural criteria for climate refugee value

The design philosophy is based on a human-centered and regenerative approach that addresses both immediate emergency needs and long-term recovery, with a clear focus on architectural value for climate refugees. The primary objective is to create architecture that supports dignity, safety, and a sense of identity under temporary living conditions.

Dignity and psychological comfort are addressed through architectural criteria that prioritize privacy, daylight, and ventilation. Each housing unit provides a well-ventilated and daylit interior while avoiding the repetitive uniformity typical of refugee camps. Instead, the layouts emphasize personal space and establish a

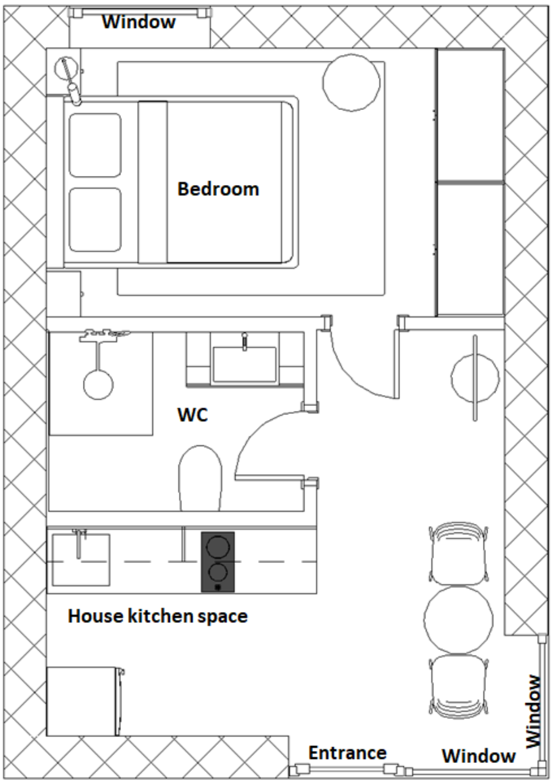

Figure 1. Detailed layout of the residential module

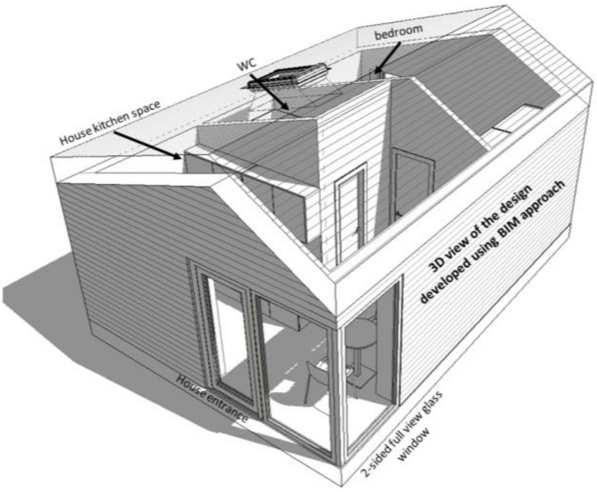

Figure 2. 3D view of the residential double module

hierarchy between private, semi-private, and shared zones, reinforcing residents' well-being and autonomy. Generous window openings, glazed entrance doors, and a roof-level window in the sanitary unit enhance the quality of natural light and improve overall spatial comfort without relying on artificial systems.

Furthermore, research in the fields of post-disaster architecture and humanitarian architecture emphasizes that community-oriented spatial planning, such as communal kitchens, open gathering spaces, and shared sanitation modules, can strengthen social cohesion and community-led recovery processes, transforming temporary shelters into vibrant social infrastructures. In line with this approach, the proposed modular system not only acts as a response to emergency housing needs but also as a platform for community resilience, allowing residents to regain a sense of normality, activity, and belonging in transitional conditions.

Aesthetic and spatial identity contribute to the architectural value of temporary housing by reinforcing a sense of home. The architectural expression is intentionally restrained, prioritizing functional clarity and emotional warmth. An asymmetrical roof form introduces visual variation while reinforcing a sense of shelter, while the combination of natural wood surfaces and anthracite window frames creates a familiar and calming domestic atmosphere that supports dignity and acceptance in temporary living environments.

3.3 Material selection to incorporate human aspects

Material selection is essential for addressing human needs in temporary housing for climate refugees. In addition to structural performance, materials influence indoor comfort, health, and psychological well-being. Studies in humanitarian architecture show that healthy indoor environments and natural materiality support emotional stability and adaptation of displaced populations [24][25].

Bio-based materials such as wood and straw contribute to improved indoor air quality and moisture regulation due to their breathable properties [7][9]. These characteristics help maintain stable indoor conditions and reduce dependence on mechanical systems, which is especially important in temporary and emergency housing. Research also indicates that natural materials create a more familiar and non-institutional atmosphere, positively affecting residents' mental well-being [26].

The use of EcoCocon straw-based prefabricated panels supports a human-centered design approach by combining high thermal insulation with vapor permeability and low environmental impact [3]. Thermal stability reduces stress caused by climate extremes, while renewable, low-carbon materials align with ethical and sustainability principles relevant to long-term displacement scenarios.

The structural and envelope system is based on EcoCocon straw-prefabricated panels used for both walls and roofing [4]. These panels are carbon-negative, offer high thermal insulation performance (U-value ≈ 0.12 W/m²K), and remain vapor-permeable while achieving a high level of airtightness. Interior partition walls are designed as lightweight gypsum board systems, allowing flexible space planning and ease of modification over time. Construction is based on a dry-assembly process, eliminating the need for wet construction methods or heavy machinery. This enables fast on-site installation as well as straightforward disassembly when relocation is required, aligning with the project's sustainability and circularity objectives.

3.4 User experience: Contractors, owners, and Humanitarian organizations

User experience in temporary housing systems for climate refugees involves several stakeholder groups, including contractors, owners, and humanitarian organizations. For contractors, modular construction systems must ensure clear assembly logic, standardized components, and minimal reliance on specialized equipment. Prefabricated panel systems, such as straw-based EcoCocon panels, support dry construction processes, which simplify on-site work and improve construction reliability in emergencies and remote contexts [4][7].

From the owners and project coordinators' perspective, adaptability and resource efficiency are key factors. Modular housing solutions that allow reconfiguration, reuse, and relocation improve long-term value and operational flexibility. This approach also results in cost savings for owners, as the housing units are designed for repeated assembly and multiple life cycles rather than single-use deployment. Research in modular and off-site construction highlights that standardized systems reduce maintenance complexity and support scalable deployment in humanitarian housing projects [6].

Humanitarian organizations act as coordinators between residents, local authorities, and technical partners. Organizations such as Okanagan 4 Ukraine focus on community support, integration, and well-being of displaced persons through coordinated services, partnerships, and local engagement [8]. Their activities demonstrate that housing solutions must not only provide shelter but also enable social interaction, access to support services, and community-building. Therefore, ease of deployment, flexibility, and compatibility with humanitarian operations are essential design criteria for temporary housing systems.

4 Development of a digital design toolkit

4.1 Integration of BIM and MR

The integration of BIM and MR is executed through a self-developed Low-latency Mixed Reality Design Platform (LMRDP), which is discussed in detail in 4.2. The BIM model of the climate refugee housing, together with local climate data (temperature, wind, etc.), adapted to it and available cost-effective materials, is transferred to Unity using a customized Revit add-in and finally deployed to Microsoft HoloLens-2 for visualization and interaction in the MR environment. This add-in utilizes the Revit API to extract high-fidelity geometry and material data, exporting them as OBJ and MTL files to a central cloud WebSocket server.

The integration is completed within a 3D game engine (Unity), where the digital assets are reconstructed into a digital dashboard. By leveraging the Microsoft MRTK-3, the platform enables spatial awareness and hand-tracking interactions, allowing users to manipulate the model (scale, rotate, and translate) in a real-world physical context. This workflow ensures that complex architectural and environmental data from the BIM environment is not only visualized but is also interactive and actionable for on-site decision-making.

Furthermore, the toolkit integrates the digital dashboard directly into the MR application. This dashboard can link the immersive model to any web-based platform, offering the automation features of the dashboard. The interface of this digital dashboard is shown in Figure 3.

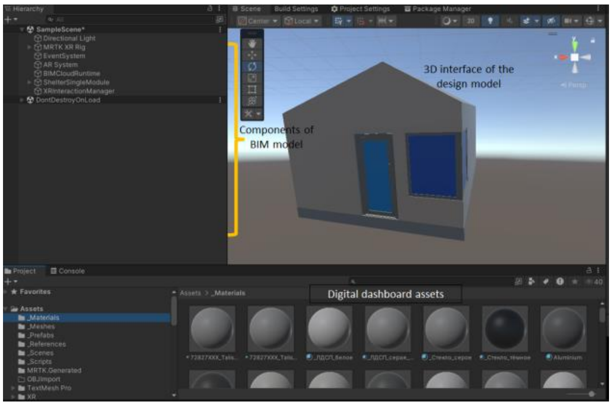

Figure 3. Digital design dashboard of the integrated BIM system in a 3D game engine

4.2 Open-source design toolkit

The LMRDP is developed as an open-source toolkit to facilitate collaborative design among architects, engineers, and humanitarian organizations. The architectural backbone of the toolkit is a Node.js WebSocket server hosted on a remote Ubuntu instance on the Amazon Web Services platform, which enables persistent, real-time communication between distributed clients. This configuration replaces traditional, asynchronous file transfers with a low-latency pipeline capable of transmitting binary data in sequential 8KB chunks, ensuring that model updates are synchronized across the design team instantly.

To lower the barrier of entry for the stakeholders, the toolkit includes a customized "WebSocket Connector" plugin for Unity. This plugin provides a dockable interface that allows users to list, preview, and import BIM models from the server with a single click, automatically parsing the OBJ/MTL data into prefabricated Unity assets, as shown in **Error! Reference source not found.**. By providing a unified interface for real-time data exchange and environmental analysis, the LMRDP democratizes access to sophisticated design tools, allowing for the rapid development of affordable and sustainable climate refugee housing solutions in humanitarian contexts.

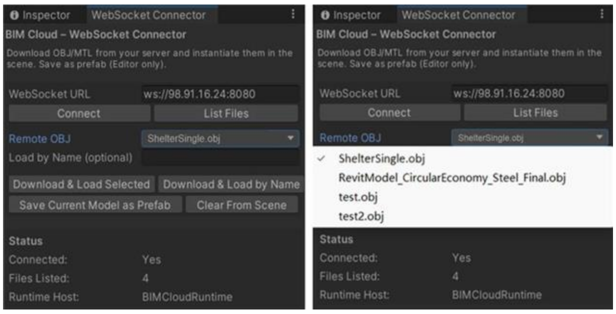

Figure 4. Customized Unity plugin dockable panel interface to enable WebSocket connection

4.3 Immersive user experience

The BIM model of the climate refugee housing design was imported into the Unity engine using a customized Revit add-in and a self-developed Unity plugin. This workflow allows both geometry and basic information to be transferred from Revit to a real-time 3D environment. The Unity interface was then integrated with the MRTK-3 and deployed to the MR headset (HoloLens). This setup enables MR visualization and interaction with the housing model in the real world.

The model can be visualized in Figure 5 in reality at a 1:1 scale. The virtual model of the building is aligned with the physical environment, so its size and position match real-world conditions. Users can move and rotate the model using hand gestures supported by the MR headset without any physical controllers. This makes the interaction more natural and easier to learn. Users can quickly test different positions and orientations of the building on site.

After placing the model, users can either walk around it to view the exterior from different angles or walk directly inside the building. The experience is similar to entering a real house. The interior includes key elements such as chairs, tables, WC fixtures, and a complete kitchen layout. All objects are shown at real scale. This helps users understand room size, ceiling height, and the distance between furniture items.

The immersive view allows users to better understand space and physical features. Circulation paths and room connections become easier to understand. Users can check whether the living space feels comfortable and practical. This is difficult to achieve with 2D paper drawings or screen-based 3D models. For climate refugee housing, this is especially important because such projects require efficient use of space and must provide safe and dignified living conditions.

Overall, the MR system turns the BIM model into an interactive and reality-based experience. The housing design is no longer only a digital file. It becomes a life-size virtual model that can be explored with realistic features. This enhances communication between designers, contractors, and owners. It also helps users to better understand the design layout. By combining BIM, Unity, and an MR headset, the workflow provides a practical way to evaluate spatial quality and usability at an early design stage.

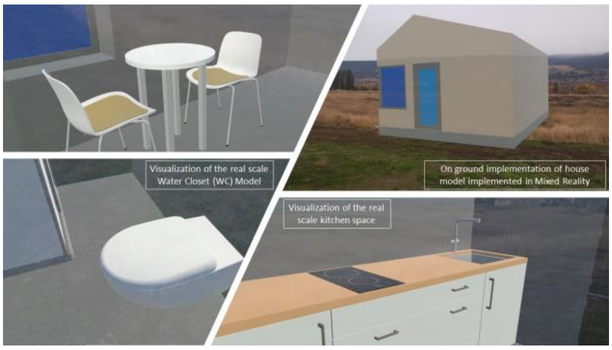

Figure 5. Visualization of the climate-displacement housing design model in MR at 1:1 scale

5 Results and discussion

The study evaluates the performance of a climate-resistant housing design in terms of adaptability to varying climatic and topographical conditions, life-cycle flexibility, and logistical efficiency. The potential outcomes of the proposed approach illustrate that the use of bio-based prefabricated panels facilitates multi-cycle reuse, simplifies transportation and assembly processes, and enhances environmental sustainability. Furthermore, the integration of modular planning and off-site fabrication improves construction efficiency while contributing to improved living conditions, including thermal comfort, spatial flexibility, and social adaptability for occupants.

The study also emphasizes that the proposed modular housing system effectively combines architectural, environmental, and human-centered criteria to meet the needs of climate refugees. The analysis indicates that the use of prefabricated bio-panel systems allows for rapid deployment of housing, adaptation to different climatic and topographical conditions, and use over multiple life cycles. Modular logic allows housing units to function independently or as part of larger settlements, supporting scalability and flexible community formation depending on emergencies.

In addition, the research also focuses on the human aspect of design and how to make people feel safe, comfortable, and part of a community even after losing their homes. To enhance user experience in the design approach, a digital toolkit using MR and WebSocket has been developed. A high-fidelity BIM model of housing design, with local climate data (temperature, wind, etc.), is integrated into an MR environment through a self-developed low-latency MR design platform using Revit API, WebSocket protocol, and the Microsoft MRTK-3. Thus, the integration of this digital design toolkit emphasizes that the system offers clear advantages for contractors, owners, and humanitarian organizations by reducing on-site labor requirements, simplifying logistics, and enabling cost-effective reuse. These findings are consistent with existing research on modular and off-site construction, suggesting the relevance of the proposed approach for scenarios of population displacement following disasters and due to climate change.

Moreover, a detailed comparative analysis of MR-based design review against conventional methods, including user studies and quantitative performance metrics, has been conducted as part of a parallel study and will be reported separately to maintain the focus of the current work.

6 Conclusions

The increasing displacement of populations in climate-affected areas requires rapid, adaptable, and sustainable housing solutions. To address this challenge, this research developed an immersive (Mixed Reality-enabled) digital toolkit that integrates modular design principles, BIM parametric designs, and immersive visualization technologies.

The study utilized modular housing design based on prefabricated bio-panel systems as an effective response to the challenges associated with the temporary accommodation of climate refugees. The proposed approach increases construction efficiency through dry assembly methods, reduces on-site labor requirements, and allows for rapid deployment and relocation of buildings in different climatic and topographical conditions. Moreover, modular design supports the principles of reuse, scalability, and circular construction, while the choice of architecture and materials enhances indoor comfort and social well-being.

In addition, a digital toolkit using MR and WebSocket is developed to enhance the visual experience of stakeholders. The parametric housing design, including the local climate data (temperature, wind, etc.) and available cost-effective materials, is integrated into an MR environment through the low-latency MR design platform using Revit API, WebSocket protocol, and the Microsoft MRTK-3. By bridging the gap between static architectural data and immersive environments, the toolkit provides a platform for stakeholders to visualize, iterate, and optimize climate refugee housing solutions in real-time.

The proposed design workflow allows stakeholders to interact with housing designs in real time, enabling interactive exploration and collaborative decision-making, especially related to cost-effective material selection. By using MR-based solutions, the toolkit provides an intuitive and engaging platform for designing climate-resilient housing that is both cost-effective and context-sensitive.

Although the study has presented some promising outcomes, it still has some limitations. The proposed system has been evaluated at a conceptual and prototype level, and it still lacks some field implementation or stakeholder-based validation. To address these limitations, future work will focus on conducting field testing, engaging stakeholders (e.g., Okanagan 4 Ukraine, Habitat for Humanity), and performing quantitative evaluations to further evaluate the field implementation and validation of the proposed approach.

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