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Retrofit with residents: proposed locally responsive participatory method for technical thermal retrofitting of public housing in the United Arab Emirates

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Abstract

Purpose – This research aims to explore the potential for this proposed locally responsive and participatory thermal retrofitting method for the existing public housing in the United Arab Emirates (UAE) that combines the technical development of thermal retrofitting alternatives and genuine engagement of Emirati residents in the process of the selection of the appropriate technical retrofitting system for their houses through an advanced e-participatory process.

Design/methodology/approach – The existing public housing stock in the UAE needs to be thermally retrofitted to achieve the targeted operational energy efficiency benchmarks. Due to the absence of a comprehensive, locally responsive and participatory thermal retrofitting strategy for this sector, the research developed and explored a five-phase thermal retrofitting method that starts with developing alternative systems for thermal retrofitting applied to a typical Emirati single-family public housing model as a representative case study. These alternatives are developed into building information modeling (BIM) models through a BIM platform that works as a unified platform for developing digital twin models for these alternatives in the second phase and technically assessing their reduced energy consumption using insight simulation in the third phase. In the fourth phase, the capital and operational energy costs of these alternative retrofitting systems are estimated, relying on the data fetched from the BIM models developed in the BIM platform. Finally, the performance of these alternatives is explained to a selected sample of Emirati residents through an advanced "e-participation" process utilizing an initiated immersive metaverse to help them define the most preferred retrofitting system for them based on the simply explained technical criteria for them and their social perception.

Findings – The findings emphasized the appropriateness of the proposed five-phase thermal retrofitting method and the success of engaging residents in its decision-making process through the utilization of the advanced "e-participation" process. Ultimately, this proposed method led to the identification of an agreed-upon retrofitting system that could significantly reduce energy consumption in the existing public housing by about 30%.

Originality/value – The research bridges theoretical and practical gaps of both the absence of a comprehensive technical retrofitting process and the drawbacks of conventional participatory techniques. This has been attained through introducing an innovative thermal retrofitting method for the large stock of Emirati public housing that integrates the technical definition of locally responsive thermal retrofitting systems with the advanced "e-participatory" process that helped the residents comprehend, compare and select among technical thermal retrofitting alternative systems for their houses.

Keywords UAE, e-participation, Community engagement, Sustainable housing, Single-family housing, Thermal retrofitting

Paper type Research paper

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1. Introduction

The federal and local governments in the United Arab Emirates (UAE), represented in their public housing authorities, have managed to provide decent houses based on local culture and technologically modernized standards of living for Emirati citizens, with a concentration on the low-income citizens, through ambitious public housing programs since the 1970s. Emirati public housing has been usually developed as detached/semi-detached single-family houses on one or two floors. Until 2005, public housing was generous in both the plots and built-up areas reaching approximately 2,300 m^2 and up to 430 m^2, respectively. Due to the hot climatic conditions in the UAE, these houses have had high cooling loads and hence high energy demand (Galal Ahmed, 2021). In addition, there has been a desire to mitigate the country's greenhouse gas emissions by reducing the carbon footprint of buildings including the residential sector. Unfortunately, the stock of existing public housing, which constitutes a major portion of the building sector in the UAE, is not receiving enough attention regarding its sustainability credentials, with efforts directed toward new housing projects (Galal Ahmed, 2017). This trend is affirmed by the country's commitments to achieve Sustainable Development Goals (SDGs) by 2030, especially Goal 11: Sustainable cities and communities (through making cities inclusive, safe, resilient, and sustainable), and Goal 13: Take urgent action to combat climate change and its impacts (The Federal Competitiveness and Statistics Authority, 2022).

Deep thermal retrofitting of the large volume of existing housing stock with its uninsulated external walls, single-glazed windows, and poor roof thermal insulation seems to constitute a significant opportunity for meeting these sustainability goals. Deep thermal retrofitting is widely recognized as an effective approach to reducing energy consumption and enhancing the sustainability of residential buildings, particularly in hot climates, where it focuses on improving the thermal insulation of building envelopes. Case studies from countries such as Saudi Arabia and the UAE demonstrate the importance of applying advanced insulation materials to external walls, roofs, and windows to minimize heat gain. For example, Al-Tamimi (2021) conducted a cost-benefit analysis of various thermal insulation alternatives (roof only, walls only, and both roof and walls) in Saudi Arabia, showing energy consumption reductions of 19.14%, 7.51%, and 29.77% respectively. Similarly, Tamimi *et al.* (2024) highlighted the role of Building Information Modeling (BIM) in optimizing building energy performance in the UAE, revealing that 100 mm Expanded Polystyrene (EPS) insulation reduced energy consumption by 11.82% while shading from nearby trees achieved an additional 3.84% reduction. Another study by Rababa and Asfour (2024) in Dhahran, Saudi Arabia, evaluated façade retrofit strategies, including enhanced insulation, energy-efficient windows, and shading devices, with the optimal solution involving an external thermal insulation composite system for walls, louvers on windows, and low-emissivity glazing with Argon gas, resulting in a 16% reduction in cooling energy consumption and a payback period of 14.8 years. These studies underline the significant potential of advanced thermal retrofitting measures in achieving energy efficiency and sustainability in residential buildings. Although these studies on retrofitting strategies both globally and locally in the UAE reflect the importance of the topic as it attracts growing scholarly attention, still there is a notable lack of focus on a comprehensive applied passive techniques strategy for the retrofitting of public housing envelops in the UAE, especially through using locally-produced/available construction and insulation materials.

On the other hand, achieving effective housing thermal retrofitting requires strategies that not only address technical and environmental aspects but also actively involve residents in the related decision-making processes. This can be accomplished by integrating local knowledge and community participation, ensuring that thermal retrofitting solutions are contextually relevant, socially inclusive, and aligned with the specific needs of Emirati communities (Alhaddad and Galal Ahmed, 2024; Alsherfawi Aljazaerly *et al.*, 2024). Principally, involving residents in the decision-making process has been widely advocated as an essential pillar for realizing sustainable housing (Congress for New Urbanism, 2018). When they are given control over the decisions related to their houses, residents would be able to credibly address their real needs and hence genuinely contribute to shaping their housing environment (Smart Growth Network, 2019). Such active community participation would create a greater sense of responsibility, belonging, and satisfaction toward the local built environment (McGill University, 2020; Kordi and Galal Ahmed, 2023). Recent studies emphasized the need for more inclusive participatory approaches in social housing retrofitting. For example, Elsharkawy and Rutherford (2018) highlight that the active engagement of residents in decision-making leads to improved energy efficiency outcomes and greater resident satisfaction in retrofit projects. Similarly, research by the UK Government (2017) found that the lack of community input often results in retrofit solutions that fail to meet residents' actual needs, reducing adoption rates. These findings demonstrate that participatory processes tailored to local contexts are essential for the success of retrofitting interventions. Moreover, evidence from community-led retrofitting initiatives in the UK suggests that integrating residents' feedback into the design and implementation stages enhances the functionality and acceptance of energy-saving measures (Jansson-Boyd *et al.*, 2017).

Despite this recognition of the importance of community involvement in deep thermal retrofitting, there is almost no research work that tackled the issue of the absence of a viable and genuine participatory method for residents' involvement in the decision-making process of the selection of the deep thermal retrofitting techniques for their existing houses in the UAE or even the whole Arab Gulf region. Accordingly, there is a desperate need for a viable participatory method that enables Emirati residents to be consulted about any possible professionally developed solutions for deep thermal retrofitting techniques tailored for their existing public housing, especially with the evident shortcomings of conventional participatory techniques. Conventionally, community participation in housing decision-making processes in general has been facilitated through various verbal and/or visual techniques. First, the verbal techniques commonly include interviews, focus groups, and "speak out" meetings, where officials can listen to members of the local community, and they mutually ask and answer questions (Ministry of the Environment - New Zealand Government, 2009). Unlike verbal techniques, visual techniques, including interactive displays made up of architectural and construction plans, photos, etc., have been usually better in encouraging the involvement and interaction among the concerned stakeholders where all views and ideas of the participants are displayed for all (The Involve Foundation, 2018).

As for the thermal retrofitting process of public housing in particular, recent studies emphasized the need for more inclusive participatory approaches in this process. For example, in their study about the Energy-efficient retrofit of public housing in the UK, Elsharkawy and Rutherford (2018), evaluated retrofitting using a "before-and-after" questionnaire-based survey. This method effectively captured residents' feedback, improving indoor conditions and achieving moderate energy savings. However, behavioral factors limited cost reductions, and while the surveys successfully gathered valuable insights, the process lacked deeper engagement, preventing a comprehensive alignment of retrofitting solutions with residents' needs. Still in the UK, Charles *et al.* (2025) examined retrofitting and energy justice in a UK public housing estate undergoing regeneration. Through semi-structured interviews with some residents, the study assessed justice dimensions within the retrofit process. While retrofits improved energy efficiency and reduced costs for some residents, issues like mismanagement and insufficient procedural inclusion created barriers to meaningful participation. Engagement events offered limited feedback opportunities and were perceived as tokenistic, undermining equitable outcomes. The study emphasized the importance of inclusive participatory processes to achieve retrofit justice and enhance energy equity. In a third study about public participation in energy-saving retrofitting of residential buildings in China, Wenling Liu *et al.* (2015) analyzed three retrofitting models in Beijing using a mixed-method approach of interviews and surveys. The study demonstrated that higher resident participation during the planning and implementation phases led to increased satisfaction and better energy-saving performance. However, despite its success in fostering decision-making participation, the involvement was limited to the planning and feedback stages, missing opportunities for real-time collaboration during the retrofitting process. In a fourth study, Yaduvanshi and Park (2023) reviewed 66 retrofit programs in the US and analyzed social media data to highlight participation methods like Do-It-Yourself (DIY) audits, professional audits, feedback mechanisms, and community engagement. The study introduced the concept of the "Citizen Building Scientist," emphasizing proactive citizen participation. While the study advanced participatory concepts and highlighted diverse involvement methods, it did not explore dynamic, interactive engagement during the actual thermal retrofitting process. Table 1 concludes the main conventional participatory methods followed in these above-mentioned studies.

While these conventional participatory methods can provide basic engagement, they lack the dynamic and immersive qualities that can significantly enhance residents' understanding and interaction. This limitation is particularly pronounced in technical processes such as thermal retrofitting of houses, where real-time feedback and spatial exploration are critical (Alizadehsalehi and Yitmen, 2021; Noroozinejad Farsangi *et al.*, 2024). The reliance on presenting hardcopies or softcopies of 2D and/or 3D drawings of the house retrofitting techniques in participatory meeting sessions might not solve the technical barrier hindering effective and comprehensive residents' participation, simply because these tools cannot help lay people visualize the retrofitting work in its actual dimensions and technical layers or components (Reinwald *et al.*, 2014; Shareef and Galal Ahmed, 2024). On the other hand, these conventional participatory methods may not sufficiently overcome the socio-cultural barriers that hinder many Emirati residents, especially women, people with mobility restraints, and the elderly, from actively taking part in participatory meetings (Galal Ahmed *et al.*, 2022). So, it is obvious that these conventional participatory techniques may not be sufficient to address complex technical and socio-cultural challenges in retrofitting public housing, especially in the UAE. This makes the need for developing participatory techniques that actively involve residents throughout the retrofitting process critical to achieving sustainable and equitable outcomes of the deep thermal retrofitting process in the existing public housing in the UAE.

To bridge this gap, this research examined an innovative technique dubbed "e-participation" which employs a Digital Twin (DT) and Virtual Reality (VR) in an initiated metaverse immersive digital environment to overcome the technical and socio-cultural barriers associated with the conventional participation methods through offering interactive, dynamic and real-time feedback through the virtual immersive experience that makes the proposed thermal retrofitting techniques much more comprehensible for non-expert residents. So, this innovative e-participation process could foster more inclusive and impactful

Table 1. Summary of the conventional participation methods and approaches in public housing retrofitting in some recent studies

Participatory method	Example: study title	Authors	Year
Quantitative *survey method*: Surveys capturing residents' experiences and attitudes	Energy-efficient Retrofit of Social Housing in the UK: Lessons Learned from a Community Energy Saving Programme in Nottingham	Elsharkawy and Rutherford	(2018)
Interview method with neighborhood workers and resident surveys	Public Participation in Energy Saving Retrofitting of Residential Buildings in China	Wenling Liu *et al.*	(2015)
Quantitative *text mining of social media* data: DIY audits, professional audits, feedback mechanisms	Citizen Building Scientist? The Opportunity and Challenge of Citizen Involvement in Building Retrofits	Yaduvanshi and Park	(2023)
Qualitative *semi-structured interview*: with 22 residents	Exploring Impacts of Retrofits with Social Housing Residents in Northwest England	Charles *et al.*	(2025)

Source(s): Table created by authors

retrofitting practices, paving the way for sustainable and equitable outcomes. As the first component of this proposed e-participation technique, DT is defined as a digital representation of a real-life physical object that aims to provide constant feedback about building performance. In the architecture, engineering and construction (AEC) industry DTs are live replicas of buildings that bring together design, construction, and real-time operational data. Through DTs, architects and professionals may run simulations of real-life scenarios to "test drive" buildings at the design stage, where users could virtually walk through the building (Sun, 2021; Housing Technology, 2022; Duch-Zebrowska and Zielonko-Jung, 2021; Ghansah, 2024). In this research, DTs incorporate 3D BIM modeling with databases that store building information for the selected case study house before retrofitting and for each of the retrofitting alternatives, as detailed later (McHale, 2022; Leete, 2022).

Second, VR is a visualization technology that offers a three-dimensional digital medium, which can be used to develop and review design options in any design or construction stage (Bouchlaghem *et al.*, 2005). VR technologies support effective community participation through a true-scale immersive digital experience (Ho, 2019). For this study, the advanced IrisVR application was employed to convert BIM models into real-time rendered virtual environments, enhancing interactivity and immersive spatial presence for participants (Prospect, 2024). Users accessed these environments using Meta Quest Pro, a high-end mixed-reality headset developed by Meta (2024), designed for an effective immersive VR experience. Pointing out the social responsibility of architects towards their communities and the response to the call to reach SDGs by 2030, Kolata (2022) affirmed that when more people test out the design of a project in VR, the more likely it is that it will work well when it is built. In many housing projects, the stakeholders did not fully understand the design based on 2D or 3D drawings but through the VR experience, architects would be able to change different aspects of designs as needed based on the residents' feedback and implement these required changes on the design before construction.

The third component is the metaverse which is the name given to an immersive, collective, and hyper-realistic virtual environment, where people will be able to interact together using 3D customized avatars (Matoso, 2022). Through metaverse platforms such as Wild, Microsoft Mesh, and Prospect IrisVR, DTs of buildings could be hosted (Sun, 2021). The novel e-participation technique proposed in this research merges the DT in the form of both a detailed layered wall section and a complete 3D BIM model for each proposed retrofitting method, as detailed later. Then, these partial and complete DTs are transferred into VR-models which are located next to each other in a simplified initiated metaverse immersive environment through the IrisVR platform. The metaverse technology in this context integrates VR into a shared, immersive digital scale 1:1 environment, enabling residents to engage in real-time, collaborative discussions with the researchers. This capability represents a significant departure from existing conventional participatory methods by offering interactive, data-driven experiences that allow participants to dynamically engage in discussions with interviewers and confidently select the appropriate thermal retrofitting strategies for them. Its scalability lies in the increasing affordability of VR modeling applications and devices, making it accessible for broader adoption across diverse housing retrofitting projects (Noroozinejad Farsangi *et al.*, 2024). Table 2 summarizes the key terms and technologies used in the proposed e-participation process, providing clear definitions for each component of it. Meanwhile, Figure 1 illustrates the e-participation process as applied in this study, showcasing the integration of DT and VR into the initiated metaverse environment.

The integration of BIM to facilitate the energy simulation, and then to integrate it in the form of DT and VR-ready models in an initiated metaverse for simultaneous collaboration, represents a novel approach to digital transformation and virtual environments compared to the recent studies in the field (see for example, Grieves and Hua, 2024; LeewayHertz, 2024; McKinsey and Company, 2022). In this research, merging BIM, DT, and the metaverse achieved dual purposes of energy simulation and collaborative participation offering a groundbreaking framework for real-time decision-making and immersive engagement. It

Table 2. Definitions of key terms used in the e-participation process

Term	Definition
E-participation	A digital process employs a Digital Twin (DT) and Virtual Reality (VR) into a metaverse digital environment to overcome the technical and socio-cultural barriers associated with conventional participation methods for better decision-making
BIM	Building Information Modeling: A software for creating and managing digital models of buildings with detailed design and data
DT	Digital Twin: A virtual representation of a physical object or system created using BIM used for analysis and simulation
IrisVR	A software platform used to convert 3D BIM models into an immersive real-time rendered environment
VR	Virtual Reality: An immersive technology that creates a 3D virtual real-time rendered environment for users to explore and interact using IrisVR software
Meta Quest Pro	A high-end mixed-reality headset developed by Meta, offering advanced features for immersive VR experiences, focusing on productivity and collaboration
Metaverse	A shared, virtual space where users interact in real-time through avatars for collaboration and experiences using IrisVR software. Participants experienced these environments through Meta Quest Pro,

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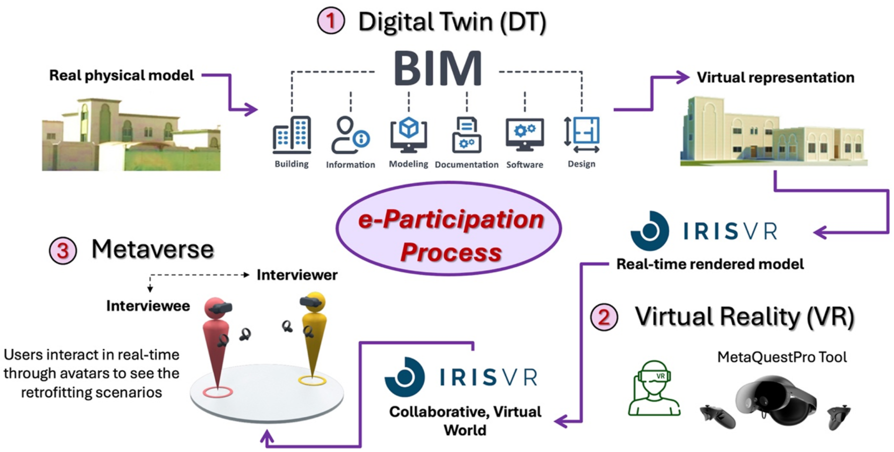


Figure 1. The proposed e-participation process integrating DT and VR into the initiated metaverse immersive and collaborative scale 1:1 digital environment facilitating user engagement in discussing and selecting the appropriate retrofitting scenario(s). Source: Figure created by authors

addresses the limitations of previous studies by demonstrating the practical feasibility of these integrations and their ability to transform digital workflows in the AEC industry. Furthermore, it uniquely positions BIM as the core platform for both simulations and metaverse collaboration, filling a critical gap in the literature where such unified implementations have not been proposed or tested before, as no comprehensive study has yet integrated BIM, DT, and the metaverse, particularly in the context of housing thermal retrofitting.

2. Research objectives and questions

As revealed from the conducted literature review above, there are no clear thermal retrofitting proposals that comprehensively utilize thermal insulation in the existing public housing stock in the UAE through commonly applied construction materials and fixation techniques in the local construction market. So, this necessitated that the research should start with a selection process of alternatives for retrofitting systems. Then, due to the absence of residents' involvement in the decision-making of the retrofitting process of their houses, an advanced e-participation process was proposed to overcome the setbacks of the conventional participatory techniques. Accordingly, the aim of this research is twofold. The first, is to develop a proposed locally responsive and participatory thermal retrofitting method through consecutive phases that integrates both the technical determination of alternatives of retrofitting systems derived from the best locally available construction materials and specifications in the UAE, on the one hand and the genuine involvement of the residents in the selection process of the most preferred alternative for them through a proposed "e-participatory" process, on the other hand. Second, is to assess the suitability of this proposed method when applied on a widely developed model of public housing by the federal Sheikh Zayed Public Housing Program, with normally high energy consumption rates.

Figure 2 illustrates a simplified chart of this proposed sequential five-phase method. Phase 1 includes the selection of the construction components of the locally responsive alternative retrofitting systems and the utilization of a unified BIM Platform with available built-in plugins to feed into the following phases by transforming these theoretically determined alternatives of thermal retrofitting systems into accurate BIM models. Phase 2 encompasses the development of the DT models of alternative retrofitting systems to showcase the technical details of each system and its full application on the selected house model. Phase 3 has the conducted Energy Use Intensity (EUI) simulations. Phase 4 includes the estimated capital and operational energy cost of the alternative retrofitting systems. Meanwhile, Phase 5 contains the conducted and assessed e-participation experience as an innovative participatory process enabling the selected sample of Emirati residents to take part in the decision-making process related to thermal retrofitting of their houses.

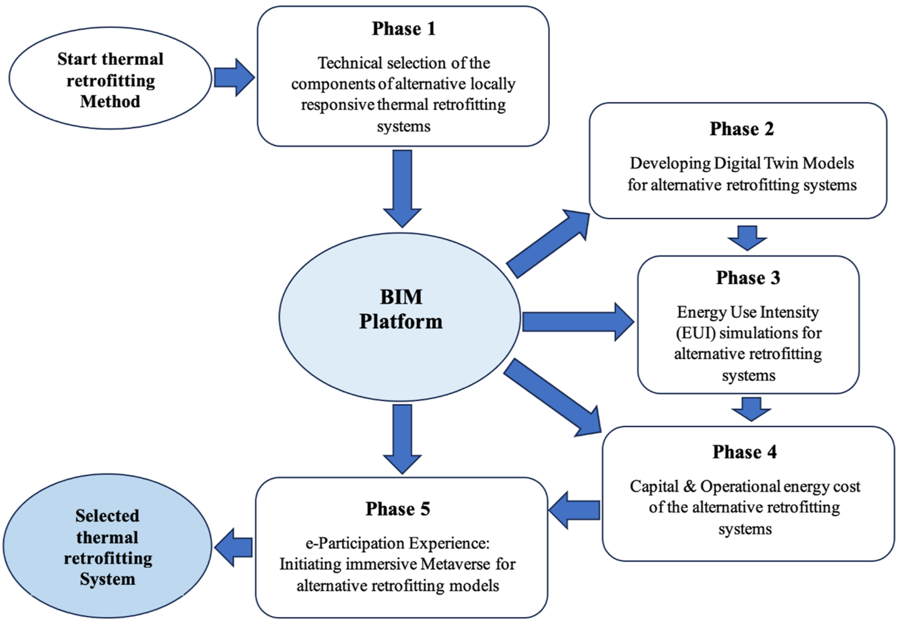


Figure 2. A simplified chart for the proposed locally responsive and participatory thermal retrofitting process with its sequential five-phase activities. Source: Figure created by authors

Accordingly, the research poses four questions. First, what are the specifications, capital cost, and expected operational energy savings of the best locally available and applicable thermal retrofitting systems, that could sensibly reduce the operational energy consumption of the selected public housing model? Second, what are the main components and the operation method of the proposed e-participation process? Third, how satisfactory are the outcomes of the e-participation process as a proposed efficient community engagement method in thermal retrofitting of exiting public housing? And fourth, how could the proposed thermal retrofitting method (Figure 2) with its locally responsive technical initiation of the alternative retrofitting systems and the proposed e-participation process for involving the Emirati public housing residents be utilized as a continuous and widely applied thermal retrofitting method of Emirati public housing?

3. Research methods and investigation tools

3.1 The selected representative typical house model case study

Among the limited number of house design models, one dubbed "Type A" was intensively developed in public housing projects in the UAE since the inception of the public housing schemes especially in the 1980 and 1990s (Figure 3). This model was the most favorable to Emirati families as it has spacious and well-distributed habitable spaces with ample outdoor areas (Galal Ahmed, 2021). This makes the design of this house a suitable representative case study of the Emirati public single-family house model that appropriately fits the purpose of this research.

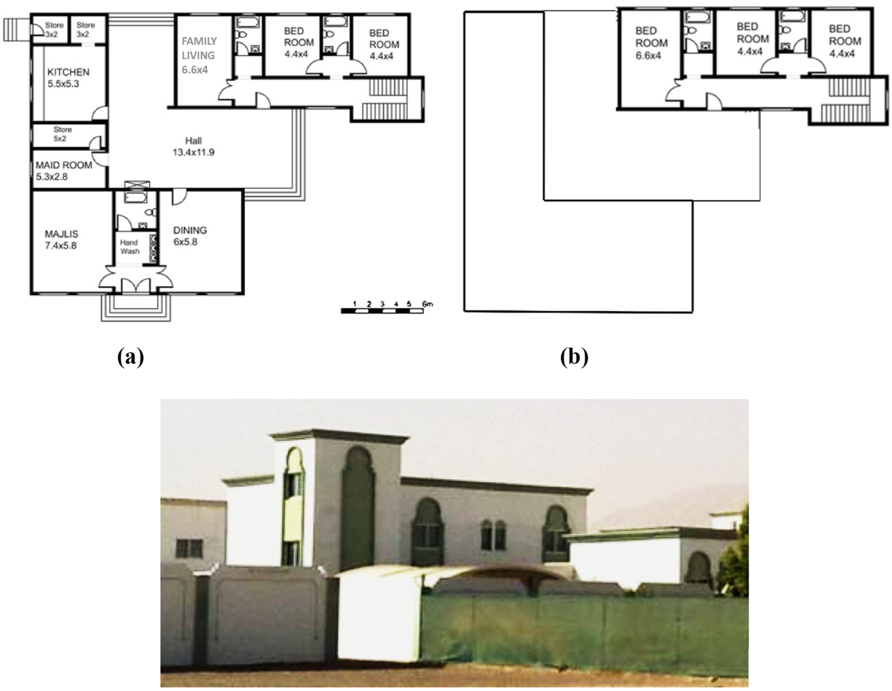


Figure 3. (a) Ground floor plan, (b) first-floor plan and (c) the façades of the selected case study house model.
Source: Figure created by authors

The drawings and construction specifications were obtained from the municipality of Al Ain, a main city with a predominantly inhabited by Emirati citizens, where this model was intensively developed. As shown in the reproduced clear and simplified drawings in Figure 3, the house has a total built-up area of approximately 430 m^2 divided into three zones; first is a one-floor male guest zone with a dining hall, a male reception hall (*majlis*), a guest toilet, and handwash basins. The second is the one-floor service zone attached to the guest zone and linked through a rear door in the dining hall. The service zone has a wide kitchen, stores, and a maid's room. The two zones compose one L-shaped structure. The third zone is a separate family zone of a two-floor structure, with two bedrooms and a family hall positioned on the ground floor and three bedrooms located on the first floor. The external walls are made of 20 cm thick concrete masonry units (CMUs) (CMU) with 2 cm painted cement plaster layers from both the external and internal sides. The aluminum framed windows are single-glazed with 3 mm thick clear glass.

3.2 Defining alternative retrofitting systems for the selected case study house model

A literature review was carried out to identify the appropriate materials and specifications for thermal retrofitting for the selected public housing model. This literature focused on key criteria such as energy efficiency, sustainability, cost-effectiveness, and suitability for the local climate. This was followed by a comprehensive local construction market search, engaging contractors and suppliers of construction materials and systems applicable to thermal retrofitting of houses. This market search aimed to gather realistic data about the material availability, technical specifications, construction costs, durability, and maintenance requirements. Initially, three well-known contractors specialized in retrofitting projects in the UAE housing sector were consulted including a Senior Engineer, an Executive Director, and a Project Manager, to identify the most efficient and commonly used, or could be used, thermal insulation cladding systems for retrofitting UAE public housing. Based on their extensive experience, the contractors recommended three cladding types: a stucco plaster layer and stone tiles cladding, both over an added layer of rigid thermal insulation, and self-insulated Aluminum cladding panels. They also provided suggestions for reputable producers for each type. Following their recommendations, two products by two supplying companies were selected for each cladding type, resulting in a total of six products being surveyed in total. The suppliers, represented by their Sales Managers, Technical Directors, and Senior Engineers, were asked to provide detailed information on the best materials they offer, considering factors such as cost, size, color, etc (Table 3).

After comparing the products based on the data provided, and the recommendation that used thermal retrofitting materials should permit minimal air filtration and possess Ultraviolet (UV) stability (Aldawoud and Hosny, 2020), supplying company no. 1 was selected for using its provided products data in the simulation phase of the research. The selection criteria included cost-effectiveness, technical qualifications, and overall suitability for the retrofitting requirements. The selected materials were Limestone (known as Saudi stone) for stone tiles cladding over an added rigid insulation layer, Aluminum sandwich panel (self-insulated) for metal panels cladding, and thin-set stucco plaster layer over an added rigid insulation layer. In all selected systems added window film and roof insulation layers were applied for the simulated alternatives. Accordingly, three alternative deep thermal retrofitting systems were developed, incorporating commonly and widely used thermal retrofitting systems tailored to the local context of the selected single-family public housing case study.

3.3 EUI simulations for the case study before and after retrofitting

The efficiency of the thermal retrofitting strategy is usually measured by the reduced EUI that expresses the operation energy consumption in the simulated retrofitted house. For single-family housing, global benchmarks for the targeted EUI have been set. For example, the EUI in the "2030 Challenge" target is estimated to be as little as 57 kWh/m^2/yr (Sun *et al.*, 2018).

Table 3. Construction market search on retrofitting cladding systems in UAE with producers

Retrofitting system	Details	Supplying company 1	Supplying company 2
Stucco plaster (to be fixed over rigid insulation)	Company Location	Ajman, Dubai	Abu Dhabi
	Price per Sq.M	*35 AED*	50 AED
Stone tiles cladding (to be fixed over rigid insulation)			
	Company Location	Dubai/Abu Dhabi	Dubai
	Stone Type	Limestone (Saudi Stone)	Limestone (Turkish Stone)
	Price per Sq.M	*200 AED*	240 AED
	Standard Size	300 × 300 mm/ 300 × 600 mm	300 × 300 mm/ 300 × 600 mm
	Thickness	20 mm	20 mm
Self -insulated Aluminum cladding panels			
	Company Location	Dubai, Ajman	Dubai, Ajman
	Price per Sq.M	*70 AED*	70 AED
	Panel Width	1,000 mm	1,000 mm
	Panel Length	600 mm	600 mm
	Panel Thickness	100 mm	50 mm

Source(s): Table created by authors

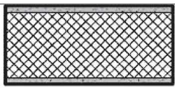
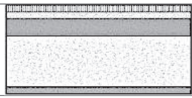
Locally, the UAE government adopted current and futuristic EUI benchmarks for thermally retrofitted single-family houses. The first is the energy performance index of 140 kWh/m^2/yr determined by the Ministry of Energy and Industry in the UAE, as a realizable target (UAE Ministry of Energy and Industry, 2018), and the second is defined by the Emirates Green Building Council (GBC) at 90 kWh/m^2/yr for energy-efficient and sustainable buildings, including single-family houses (Emirates Green Building Council, 2017). The local EUI benchmarks are adopted in this research. The construction layers for the main components of the envelope of the case study house are detailed in (Table 4), while the full DT model was digitally constructed as a 3D BIM model using the Autodesk, 2023 application (Figure 4).

Autodesk Revit application was selected as a BIM Platform producing 3D DT models and enabling the EUI assessment through its Insight plugin to simulate the expected EUI values of the three defined retrofitting alternative systems. Both the Revit BIM Platform and its Insight plugin are developed by the globally acknowledged and widely reliable Autodesk (2023) company. The climatic data of the geographic location of the case study for Al Ain city was used in the simulation process to ensure correct simulation outcomes. Also, being a built-in plugin within the BIM Platform, the Insight simulation tool uses the exact construction and finishing materials of the house envelope as defined in each simulated DT model of the house's retrofitting alternative systems. In addition, the Insight plugin employs the validated and reliable EnergyPlus (e+) engine developed by the US Department of Energy for its EUI simulations.

3.4 E-participation sessions and associated in-depth interviews

As the selected house model was the only developed model in Al Dhaher public housing neighborhood more than almost 25 years ago, this neighborhood was selected as the focal source of population from which a sample was selected for interviewing through the proposed e-participation method. As explained above, the e-participation is an innovative method

Table 4. Construction components of the case study house case study model

	Wall	Roof	Floor	Windows
R-value (m^2-K/W)	0.28	1.87	0.14	0.17
U-value (W/m^2.K)	3.55	0.53	7.05	5.74
Layers	- Outmost layer: Cement Plaster (2cm) - Layer2: CMU Hollowcore (20cm) - Innermost layer: Cement Plaster (2cm)	- Outmost layer: Cement Tile (2cm) - Layer 5: Cement Mortar (2cm) - Thermal/Air layer: Rigid Insulation (Scm) - Layer 3: EPDM Membrane (0.8cm) - Layer 2: Reinforced Concrete (15cm) - Innermost layer: Cement Plaster (2cm)	- Outmost layer: Ceramic Tiles (2cm) - Layer 4: Cement Mortar (2cm) - Layer 3: Screed (5cm) - Layer 2: Ordinary Concrete (15cm) - Innermost layer: Cement Plaster (2cm)	Single glazed window with clear glass panel and aluminum frame
Total Thickness (cm)	24	27	26	9 (for frame)
Cross Section				

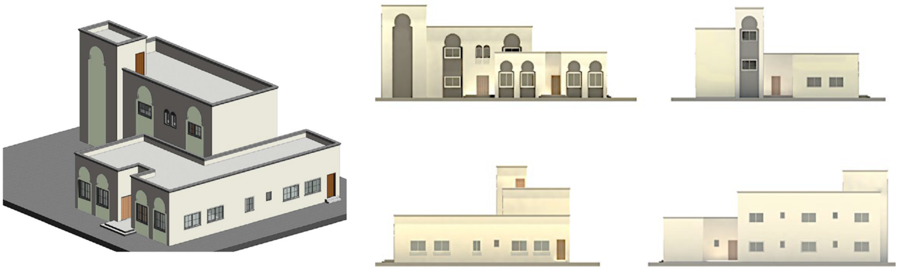


Figure 4. The developed DT 3D BIM model for the selected house case study before retrofitting. Source: Figure created by authors

developed to combine direct communication between residents and professionals in a fully immersive, interactive, and collective manner utilizing the advanced DT 3D BIM, VR, and metaverse technologies. The selection of the interviewed Emirati individuals was based on being residents in the neighborhood and the same house model as the selected case study for no less than 20 years, to ensure their familiarity with the house and the accumulated experience of thermal conditions and the utility bills paid to provide thermal comfort through air conditioning systems. Recruiting interviewees was undertaken through the reach out through personal networks to identify individuals willing to participate in the research. Interviewees were approached through direct contact by relatives and friends using a snowballing method. The snowballing sampling method was chosen due to its practicality in qualitative research, as it allows for the identification of participants who meet specific criteria through social networks (Naderifar *et al.*, 2017). On the other hand, the snowball sampling method was almost the only feasible sampling method to gain access to the residents involved in this research, clearly due to socio-cultural constraints that would have hindered the researchers from undertaking the interviews. Given the obvious limitation of the qualitative nature of the prolonged in-depth metaverse interviews, as detailed later, a sample of 30 residents was targeted. Ultimately, 21 households agreed to be interviewed and test out the virtual model. Although the sample size is relatively small, it is adequate for the objectives of the study, as the focus was on obtaining in-depth qualitative data rather than broad generalizability. This aligns with recommendations for exploratory studies where smaller, targeted samples provide detailed insights (Naderifar *et al.*, 2017). On the other hand, the prolonged time consumed in the metaverse visit and the interviews before and after it, would make a larger sample difficult. Also, the 21 interviewed residents gave in their responses sufficient and satisfactory answers to the posed questions. The final sample of interviewees included 14 male and 7 female residents. Despite the imbalance in gender of the sample, it was considered a success to be able to interview female residents due to the commonly conservative nature of the Emirati society.

As mentioned above, in the initiated e-participation tool, the virtual 1:1 scale model of each of the proposed retrofit alternatives was developed as a BIM, DT, and VR-ready model within a specifically initiated metaverse immersive and interactive environment. This was envisaged to overcome the technical and socio-cultural barriers associated with the conventional participatory methods as residents and professionals could mutually interact and embark on technical discussions to reach a consensus on the preferred retrofitting alternative. The metaverse interviews were conducted in three consecutive stages with each interviewee, beginning with a deliberately clear and simple introduction by the involved researcher about the alternative retrofitting systems, elucidating simply, the technical construction measures such as the materials, specification, and fixation methods of the added layers to the external walls of the retrofitted house. Also, the expected capital cost and energy savings for each proposed retrofitting technique were clearly explained. Visual aids such as images for the utilized retrofitting materials were employed to ensure better understanding before transitioning to the e-participation virtual metaverse environment.

In the second main stage, the interviewer guided the interviewee to wear the Meta Quest Pro VR headset, prioritizing comfort and security while utilizing the IrisVR application on the VR-ready laptop. During the immersive and collaborative metaverse session, both parties entered the virtual metaverse environment containing the DTs of the base house before retrofitting and the alternative retrofitting systems for the selected case study house. While being in this immersive environment and virtually shown to each other as Avatars, the interviewer demonstrated both the detailed construction layers and the full retrofitted house model for each retrofitting alternative. The interviewer guided the interviewee through each alternative and posed the prepared open-ended questions about the preferred retrofitting system and the rationale behind the preference through the following question: "After explaining to you all different technical specs, expected capital cost, visual aspects, and considering the percentage of the reduction in the total energy consumption of your house through each of the three retrofitting alternative systems, which one do you ultimately prefer for your house? And What factors influenced your selection of this preferred alternative?"

In the third stage, after concluding the metaverse session, a closing discussion took place where participants reflected on their preferred retrofitting alternative(s) and their potential cost and performance implications through the following three asked questions "Now after you 'virtually' experienced all the retrofitting alternative techniques, to what extent has the capital cost affected your chosen retrofitting alternative system? And how significant the government incentive would be to help encourage thermal retrofitting of your house?" Finally, participants were asked to provide feedback on their e-participation immersive experience through asking them, "Reflecting on your immersive and interactive experience within the metaverse, how effective do you find it in providing an understanding of the technical details and the visual characteristics of the potential retrofitting alternatives, especially if compared to conventional images shown to you before the e-participation session?"

On the other hand, to examine the readiness and suitability of the e-participation tools and digital environments, a pilot full e-participation interview was first conducted with a resident from Al Dhaher neighborhood. The pilot session included all stages of the e-participation process, starting with the introduction of the retrofitting scenarios, transitioning to the metaverse experience using the Meta Quest Pro VR headset, and concluding with a feedback session. This trial run allowed the researchers to assess the functionality of the involved digital tools and hence to identify the technical and logistical issues, as well as to refine the interviewing process as a whole. Finally, the collected qualitative responses to the posed open-ended questions during the three interviewing stages were qualitatively analyzed based on “coding up” of the main themes of the responses that revealed the preferences of the interviewed residents and the justifications for these preferences.

4. Results

4.1 Developed alternative thermal retrofitting systems for external walls

As discussed earlier, in the local housing construction market in the UAE, three widely applied construction systems and materials suitable for thermal retrofitting were identified and applied in the proposed alternatives of the retrofitting systems, which were assessed later through EUI simulation, as follows:

(1) Stucco plastering over an added layer of rigid thermal insulation

In the original house, a 2 cm layer of cement plaster is already applied as a finishing layer material for both the external and internal sides of the CMU walls and rendered with textured white color paint. In this retrofitting system, a layer of rigid polystyrene thermal insulation boards is firstly fixed over the existing external cement plaster finishing layer to improve the thermal efficiency of all external walls of the house. These panels are readily available in various sizes in the UAE’s construction market, with 10 cm thickness as the most used size for obtaining efficient thermal insulation (*R*-Value). After fixing the rigid polystyrene thermal insulation boards, a durable 2 cm thick stucco plastering coat is applied over a metal or plastic mesh fixed over the added rigid insulation layer (Figure 5).

One of the primary advantages of using stucco plastering as an exterior finish to protect the added rigid thermal insulation boards is its ability to withstand the harsh climatic conditions

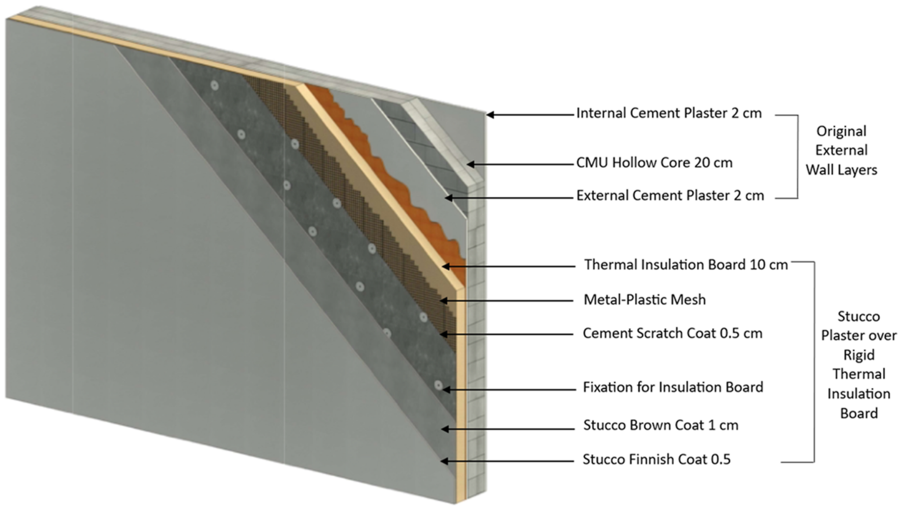


Figure 5. Details of the stucco plastering coat applied over the rigid thermal insulation boards. Source: Figure created by authors

prevalent in the UAE, due to its high resistance to heat, sunlight, and sandstorms (Zhi, 2018; Building America Solution Center, 2018; Terraco, 2023). In addition, stucco plastering is easy to patch if damaged, ensuring longevity and ease of maintenance (Building Advisor, 2019). Figure 5 illustrates the construction layers of this thermal retrofitting system for the external walls of the case study house.

(2) Limestone tiles cladding over an added layer of rigid thermal insulation

Among the popular natural stone cladding materials in the local construction market in the UAE, limestone is the most widely used especially in houses. Limestone is highly favored for housing due to its widespread availability, pleasing aesthetics, long-lasting nature, and adaptability (UAE Ministry of Energy). It represents a remarkable fusion of art and engineering, offering innovative solutions for enhancing building exteriors. When installed over rigid thermal insulation boards, thin limestone cladding tiles provide good insulation and help reduce energy costs (Sabta, 2024). Moreover, limestone is relatively easy to maintain in single-family housing, with regular cleaning and periodic sealing being sufficient to preserve its appearance and protect it from stains or discoloration. Additionally, limestone possesses natural cooling properties, making it an ideal choice for low-rise housing construction in the hot climate of the UAE (Natural Stone Global, n.d.).

The manufacturing process of the limestone cladding tiles typically involves sawing, polishing, and finishing the stone, which requires some energy input. However, the overall embodied energy of limestone wall cladding is relatively low because the material is sourced locally in the UAE, and the manufacturing process is simple compared to other materials. Figure 6 illustrates this retrofitting system that encompasses the fixation of 2 cm thick limestone tile cladding, each typically features four undercut anchors at equal distances from each of its corners to guarantee an even distribution of the load. Panel clips create the hook-on connection to a horizontal metal rail which is mechanically fixed at two points for stability and security (Scheffler, 2016). Like the stucco plastering alternative a 10 cm thick layer of rigid

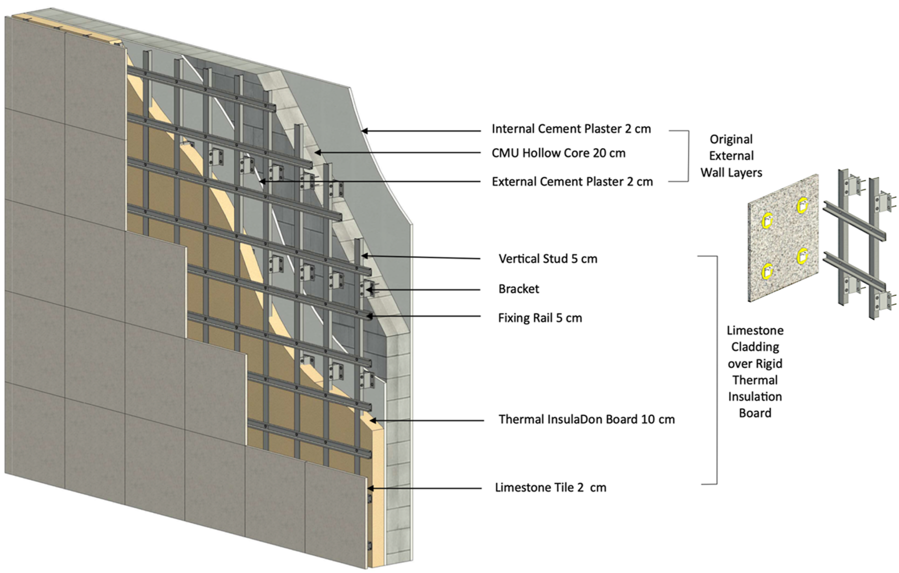


Figure 6. Details of the limestone tiles cladding over an added rigid thermal insulation layer. Source: Figure created by authors

polystyrene thermal insulation boards is firstly fixed over the existing external cement plaster finishing layer.

(3) Self-insulated aluminum sandwich panels cladding

Aluminum is a versatile material commonly utilized in external cladding applications. It can be employed in various configurations, including single flat sheet types or as part of composite or built-up systems (BSB Group, 2024). Self-insulated aluminum sandwich panels have emerged as a holistic solution for building exteriors, offering numerous benefits. Minimal maintenance is required due to their weather-resistant properties, although occasional cleaning may be necessary to preserve their visual appeal. Their relatively low embodied energy makes them an environmentally sustainable choice for construction projects. Additionally, their sleek design enhances the overall visual appeal of structures (Kausar *et al.*, 2023; Almusaed *et al.*, 2023; White Metal Contracting LLC, 2023). These panels, readily available in the local construction market in the UAE, are crafted from high-quality Aluminum material, ensuring robust resistance against weathering and corrosion that leads to long-term durability. Figure 7 shows the fixation method, components, and dimensions of the selected self-insulated Aluminum sandwich panels retrofitting system.

4.1.1 Thermal retrofitting of windows. In regions with high cooling-demand climates like the UAE, another effective retrofitting strategy involves reducing solar heat gain by applying films or coatings to the glass panes of windows. Advanced window films adhere well to the glass panes of the existing windows to significantly enhance their thermal performance by blocking up to 78% of solar heat with minimal disruption. In some cases, the solar heat gain coefficient of a high-performing window film can be reduced to as low as 0.45, compared to the typical 0.71 (Naditz, 2015). In the local construction market in the UAE, the best window film product utilizes non-metalized technology to prevent corrosion, eliminate the need for an edge seal, and avoid signal interference. It boasts high visual light transmission (71%), along with up to about 97% Infrared (IR) rejection that leads to both energy savings and increased

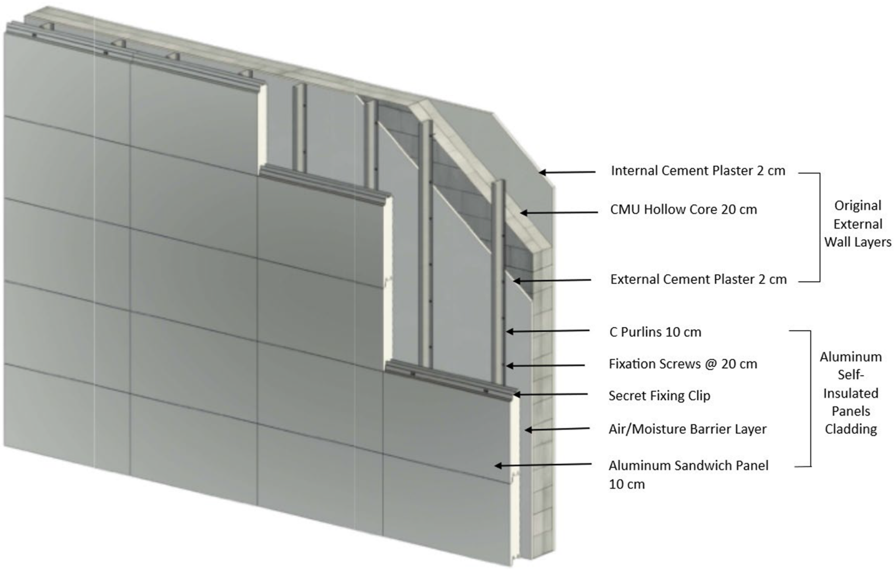


Figure 7. Details of the self-insulated aluminum sandwich panels retrofitting system. Source: Figure created by authors

comfort. With low interior and exterior reflectivity, it maintains clear views while reducing harmful UV rays that cause fading (3 M, 2024).

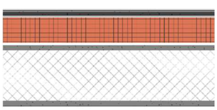
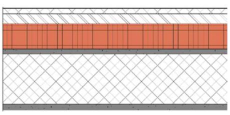
4.1.2 Thermal retrofitting of roofs. Various techniques could be applied to thermally retrofit the existing flat roofs of houses in the UAE. These mainly include the simple addition of a thermal control layer (a ballast roof with a gravel layer). The thermal control layer, which is usually made of spray Polyurethane (PUR) foam (PUR), Extruded Polystyrene (XPS) sheets with faces from cement mortar and fiberglass mesh, or rigid mineral wool boards, controls the flow of heat from the outside to the inside where the addition of exterior rigid insulation can significantly improve the roof assembly's thermal performance because it provides a continuous insulation layer. The amount of exterior thermal rigid insulation added to the roof assembly will depend on the climate zone and design goals for the retrofitted building (Purios, 2018; Adly and El-Khouly, 2022). So, R10 polyisocyanurate rigid foam insulation seems a good choice for being applied in the selected case study house due to its exceptional thermal performance, durability, and fire resistance. Also, its closed-cell foam core provides superior insulation properties while its strength and durability make it well-suited for withstanding harsh weather conditions in the UAE, including high temperatures and commonly intense sunlight (Thermal Building Products, 2024).

4.2 Energy, cost, and saving analyses for the defined alternative retrofitting systems

4.2.1 Construction details and technical specifications. The construction details and technical specifications of all selected materials of the three alternative retrofitting systems are based on the UAE's local construction market availability. Table 5 summarizes the technical specs of those three retrofitting systems and the calculated thermal performance parameters of the *R*-value (thermal resistance) and the U-value (thermal transmittance). The resulting total thickness of the external walls of the house after adding the layers of each system (as shown in Figures 3–5), is also calculated while a cross-section in the external wall for each system showing the original and added layers for each system is also presented.

As shown in Table 5, the stucco plaster system has an *R*-value of 7.67 m^2.K/W and a U-value of 0.13 W/m^2.K, with a total thickness of 378 mm. The limestone tiles cladding wall exhibits an *R*-value of 5.7 m^2.K/W and a U-value of 0.175 W/m^2.K, with a total thickness of 400 mm. Meanwhile, the self-insulated Aluminum sandwich panels cladding wall demonstrates an *R*-value of 2 m^2.K/W and a U-value of 0.5 W/m^2.K with a total thickness of 440 mm.

Table 5. Thermal insulation values and layering of the alternative thermal retrofitting systems based on the local construction market search

	Stucco plaster over rigid thermal insulation	Limestone tiles cladding over rigid thermal insulation	Self-insulated Aluminum sandwich panels cladding
R-value (m2.k/w)	7.67	5.7	2
U-value (W/m2. k)	0.13	0.175	0.5
Total thickness (cm)	37.80	40	44
Layers in a cross section in external walls			

Source(s): Table created by authors

4.2.2 Energy performance through EUI simulations. The energy simulation was conducted utilizing the Insight plugin in Autodesk Revit for the defined three thermal retrofitting systems in addition to the baseline house model before retrofitting. As shown in Figure 8, the EUI simulation for the developed 3D BIM model of the selected exiting house model before retrofitting revealed its significantly high operational energy consumption reflected in its high EUI value of 324 kWh/m^2/yr. As for the EUI simulation results after retrofitting, for the first alternative, when applying 2 cm stucco plaster layer over a 10 cm thick rigid thermal insulation layer above the existing external walls of the house, along with added R10 rigid thermal insulation boards on the roof and fixed window films on all windows, the obtained EUI value considerably dropped to 227 kWh/m^2/yr indicating a significant reduction in the operational energy consumption of the retrofitted house. For the second retrofitting alternative, when limestone tiles were cladded over a 10 cm thick rigid thermal insulation layer fixed over the external walls, and combined with R10 added roof insulation and window filming, a significant reduction in operational energy consumption was achieved with EUI value of 230 kWh/m^2/yr. This is a very close EUI value to that obtained from the first retrofitting system. Meanwhile, the third alternative retrofitting system, using Aluminum self-insulated sandwich panels cladding, with added R10 roof thermal insulation boards and window filming, the Insight simulation also indicated a considerable reduction in the operational energy consumption with an EUI value of 225 kWh/m^2/yr. This is slightly better than the first and the second alternative retrofitting systems.

4.2.3 Capital costs and savings for alternative retrofitting systems.

(1) Capital costs

The capital cost required for the development of the three retrofitting alternatives was estimated based on a detailed breakdown of expenses collected directly from the local construction market distributors through face-to-face interactions and phone inquiries during May 2024, as motioned above. First, for applying the 2 cm thick stucco plaster and its associated 10 cm thermal insulation rigid board layers on the whole house's external façades area of about 720 sq. m., with needed mesh, bitumen air barrier, and the cost of insulation, the best local market price was about 61,200 AED. Second, for the 2 cm thick limestone tiles cladding with sizes of 30 $\times$ 30, 30 $\times$ 60 cm, and with added 10 cm rigid insulation boards, the best local market price including the installation over the whole area of the house façades was about 169,200 AED. Third, for the 10 cm thick self-insulated Aluminum cladding sandwich panels, the best cost in the local market, including the installation of the panels over the whole façades, is about 70,200 AED. Based on these roughly estimated capital costs, the stucco plaster retrofitting system is the most cost-effective alternative. Table 6 summarizes the capital cost estimations for the three wall thermal retrofitting systems and Figure 9 shows the capital cost estimations for the three alternative retrofitting systems compared to each other.

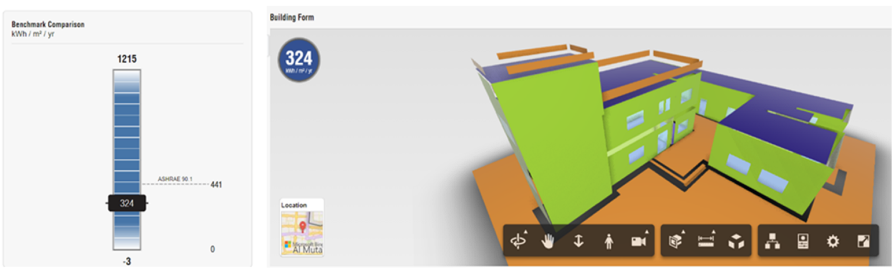


Figure 8. Insight EUI simulation result for the selected case study house model before retrofitting. Source: Figure created by authors

Table 6. Capital cost rough estimation for the three alternative thermal retrofitting systems based on the local construction market search conducted during May 2024

	Stucco plaster over rigid thermal insulation	Limestone cladding over rigid thermal insulation	Self-insulated aluminum sandwich panel cladding
Detailed capital cost (AED/Sq. m).	30 plaster+10 mesh+10 Bitumen+35 Insulation	160 supply+40 installation+35 Insulation	70 supply+30 installation
Total external wall area (Sq. m.)	720	720	720
Total cost (AED)	*61,200 AED*	*169,200 AED*	*70,200 AED*

Source(s): Table created by authors

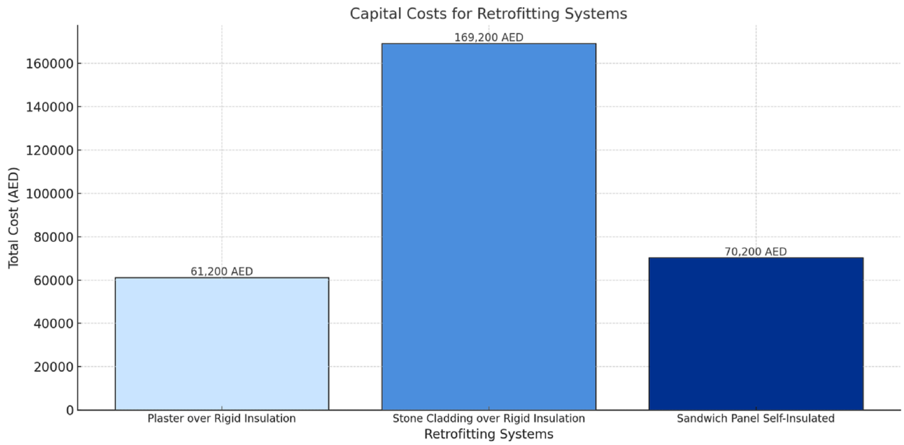


Figure 9. Comparative capital cost estimations for the development of the three alternative retrofitting systems. Source: Figure created by authors

In addition to that, the capital cost of the roof insulation and window films that are applied in all three alternative retrofitting systems was equally added to the cost of the retrofit of external walls in each alternative. The capital cost of the roof insulation, determined by multiplying the cost per square meter by the total roof area to be insulated including the cost of installation for the case study house model, would be about 70 AED per square meter. So, for the total roof area of about 250 square meters, the overall capital cost will be about 17,500 AED. Meanwhile, the capital cost of adding window films is calculated by multiplying the cost of 110 AED per square meter by the total windows area of 53 square meters. This is about 5,830 AED. These costs are added to each of the capital cost estimated for each of the three alternative thermal retrofitting systems.

(2) Operational energy cost savings

The mentioned above results of the retrofitting analysis indicated that all three retrofitting systems resulted in close substantial reductions in operational energy consumption, by 29.94% for the stucco plaster first retrofitting alternative, 29.01% for the limestone tiles cladding second retrofitting alternative, and 30.56% for the self-insulated Aluminum sandwich panels third retrofitting alternative. With the applied electricity consumption tariff in Al Ain city, Abu Dhabi Emirate, where the selected house model is developed, and considering the reduction in the electricity cost by about 30% on average after applying almost any of the three retrofitting systems, the decreased cost in monthly electricity bill would be equal to about 726 AED/month from the monthly electricity bill that currently costs about 2,420 AED before retrofitting. This gives annual savings in electricity bills of about 8,712 AED for each retrofitted house. Based on that, the payback period for the initial cost estimations of the three alternative retrofitting systems could be roughly 9.7 years for the stucco plaster with rigid insulation, 22 years for the limestone tiles with rigid insulation, and 10.7 years for the self-insulated Aluminum panels. Figure 10 illustrates the estimated energy reduction percentages and payback periods for the three alternative retrofitting systems.

4.3 Outcomes of the e-participation sessions

4.3.1 Prepared metaverse immersive and interactive visits. Figure 11 shows the VR-ready DT BIM models for the selected house after applying each of the three thermal retrofitting alternative systems as both partial layered wall sections and complete house models.

Meanwhile, Figure 12 shows the initiated metaverse environment with the planned VR-guided sequential immersive visit scenarios starting with the DT of the base model of the house followed by the arranged scenarios of the DTs of the three developed alternative thermal retrofitting systems (a, b, and c in Figure 11).

4.3.2 Pilot metaverse visits and interviews. The pilot interview with a resident in Al Dhaher neighborhood was conducted to assess the suitability of the settings of the DT BIM models and the VR measures in the initiated metaverse immersive digital environment before proceeding to the planned interviews. Table 7 explains the issues identified in this pilot interview related to the usability and effectiveness of the developed virtual environment. Accordingly, a related solution for each challenging issue was implemented to enhance the VR and metaverse experiences before rolling out to the e-participation stage (Table 7).

4.3.3 Preferred retrofitting alternatives through e-participation. Responses from each of the 21 interviewees were collected during their individual guided immersive virtual visits in the metaverse (Figure 13). As detailed earlier, each interview was conducted in three stages, the introductory stage just introduced the interviewees to the different aspects of the three alternative retrofitting systems, the second stage included the questions during the metaverse visit, and the third stage included the questions after it. During the metaverse visits, interviewees were asked to express their preferences, with justification, for the retrofitting system alternative(s). Figure 14 shows examples of the annotation tools used by the participating interviewer to facilitate the interaction and mutual discussion with the

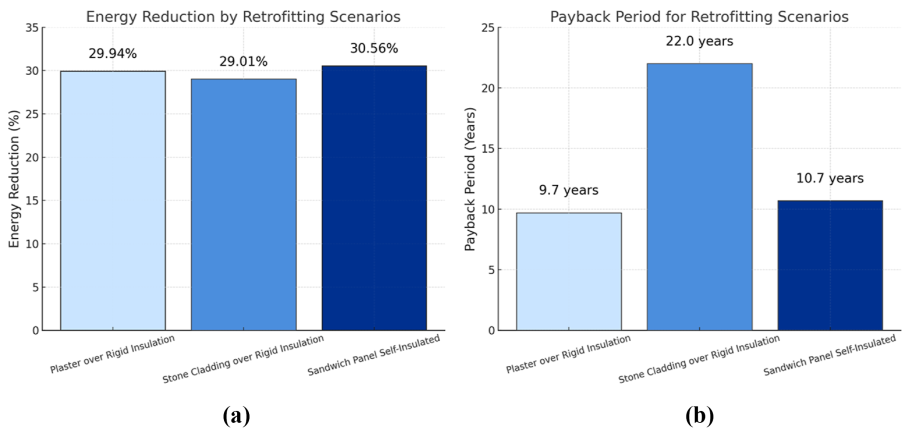
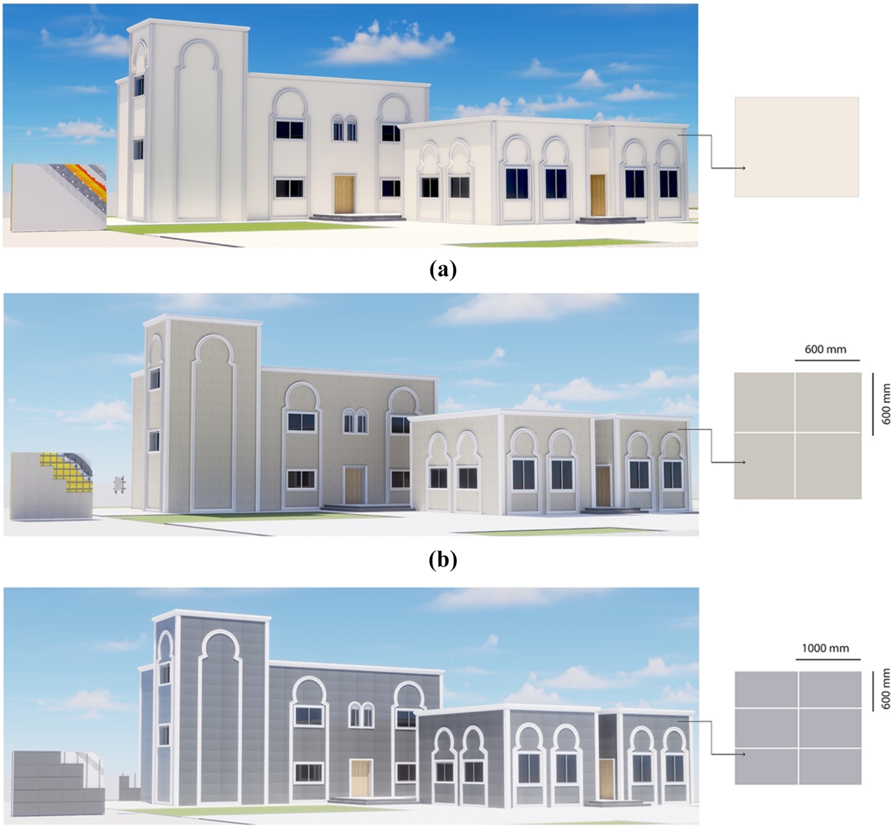


Figure 10. (a) Energy reduction percentages for the three alternative retrofitting systems and (b) payback periods for each system. Source: Figure created by authors



(a)

(b)

(c)

Figure 11. The developed VR-ready DT models for the thermal retrofitting systems; (a) stucco plaster over rigid insulation, (b) limestone cladding over rigid insulation and (c) aluminum self-insulated panels. Source: authors

interviewed residents during the immersive and interactive metaverse visits. Among the 21 interviewees, only 2 chose stucco plaster with rigid thermal insulation as their preferred retrofitting materials. Meanwhile, 11 interviewees opted for the limestone tiles cladding with rigid thermal insulation, and 8 of them favored the self-insulated Aluminum cladding, for possible thermally retrofitting their houses. After completing the e-participation session, the interviewees in the third stage got the chance to think about the capital costs and economic benefits of each of the three retrofitting systems. In their responses, the interviewees weighed the initial investment against long-term benefits, with some of them willing to pay more upfront to get more durable solutions that would reduce maintenance costs over time.

Additionally, the potential impact of possible government incentives was highlighted by many of the interviewees who expressed willingness to pursue thermally retrofitting their houses if financial assistance was provided by the local authority. Finally, the interviewees were asked about their overall comments on their e-participation experiences. Nine out of the 21 interviewees considered the initial cost of retrofitting as a major factor in their decision, still many of them preferred the aesthetic appeal of the limestone cladding over the much cheaper stucco plaster. Meanwhile, 12 participants did not prioritize cost that much. Most of the

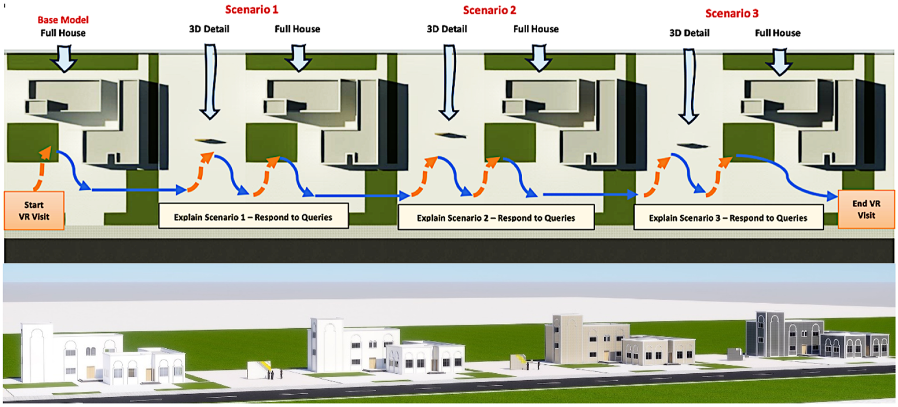
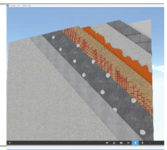
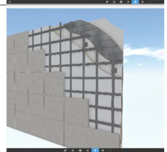


Figure 12. The initiated metaverse showing the prepared immersive sequential visits scenarios for the base model of the house and its three alternative thermal retrofitting systems. Source: Figure created by authors

Table 7. Summary of issues and solutions identified during the pilot metaverse visit and interview with one participant

	Issue	Solution	Illustration
1	Visualization difficulty experienced during the virtual movement.	Adding more camera views to easily and appropriately guide the visit of the interviewee.	-
2	Confusion arising from the similarity in color between thermal insulation panels and the Stucco plaster.	Changing the color of the thermal insulation boards to yellow to it differentiate from the color of the Stucco plaster.	
3	Low quality resolution for the stone tiles cladding.	Enhancing stone material specifications as sourced from the Autodesk Revit application.	
6	Dark color of the Aluminum sandwich panels.	Adjusting panel color to a lighter shade to show it better.	
7	Difficulty in accurately positioning the interviewee for appropriate visualization of the DTs models.	Reorganizing scenarios and adjusting camera positioning for precise placement for each DT model.	-
8	Difference VR visual fields between seating and standing positions for interviewer and interviewee.	Either ensuring both parties are seated, or both are standing to maintain VR visual consistency.	-

Source(s): Table created by authors

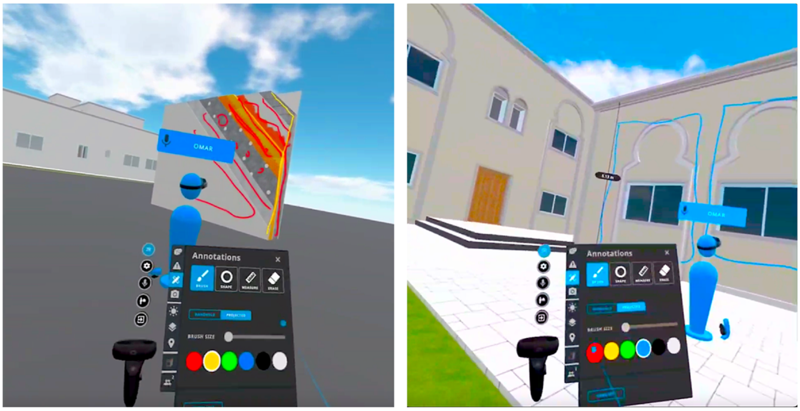
(a) (b)

Figure 13. E-participation sessions with (a) a female participant and (b) a male participant. Source: Figure created by authors

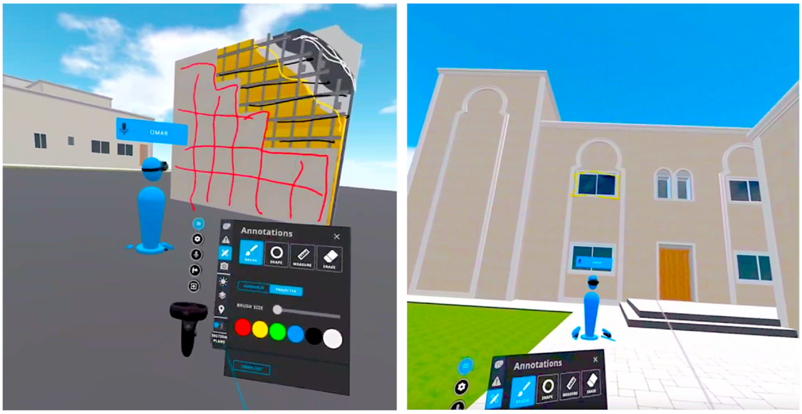
interviewed residents called for the support of local authority/government in the provision of the needed cost. As for their reflections on the e-participation experiences, they overwhelmingly supported it with some asking for some improvements. These responses are detailed in Table 8.

5. Discussion

The research suggested and assessed an innovative and participatory method that combines technical/professional development and simulations for locally responsive alternative thermal retrofitting systems on the one hand, and an innovative e-participation process, on the other hand. This combined method started with a comprehensive local construction market search that resulted in defining local context-responsive alternative retrofitting systems namely stucco plaster over rigid insulation, limestone tiles over rigid insulation, and self-insulated Aluminum panels. The following second phase was developing the DT models of these three proposed retrofitting alternatives using Autodesk Revit BIM Platform. Here are the dual benefits of using this Platform. First, it facilitated the EUI simulation of the initialed BIM models for retrofitting alternatives through its Insight plugin simulation tool. This is the third phase of this proposed method. Once the energy savings of each alternative were determined, the expected savings in electricity bills were easy to estimate and added to the calculated initial cost for each alternative. This constituted the fourth phase in the explored proposed retrofitting method, where the simulations predicted that the achieved reduction in energy consumption of the three investigated retrofitting systems would be close, with the stucco plaster as the most initial cost-efficient system with annual operational energy savings leading to a payback period of 9.7 years, followed by the self-insulated Aluminum panels cladding with a close payback period of 10.7 years, and then, with a much higher initial cost and a longer payback period of 22 years, came the limestone tiles cladding. Previous research suggested that the initial cost of the retrofitting of existing houses is a key indicator of the economic feasibility and efficiency of the selected retrofitting strategy. Also, the number of years required for each retrofitting option to recoup the initial investment through energy savings is crucial in assessing the financial viability of the retrofitting interventions (Ma *et al.*, 2012; Galal Ahmed, 2019; Balasbaneh *et al.*, 2022). The second benefit of the utilized BIM platform is that the DT models for these alternative retrofitting systems were easily converted into VR-ready models through IrisVR, another plugin tool also embedded within the platform, that was located in the



(a)



(b)

Figure 14. Examples of the immersive and interactive e-participation session examining (a) the stucco plaster retrofitting system and (b) the limestone cladding retrofitting system. Source: Figure created by authors

initiated metaverse immersive environment. This constituted the e-participation experience as the fifth and last phase of this proposed method. So, this simply means that once local context-responsive alternatives for housing retrofitting systems are defined, both their energy performance assessment and residents' participation in selecting the most preferred alternative could be facilitated utilizing the BIM Platform with its plugins: Insight (for EUI simulations) and IrisVR (for the e-participation) after creating the BIM models in it.

The research investigation outcomes proved usefulness of the e-participation as an innovative community involvement process in housing retrofitting decisions as it has overcome the technical and socio-cultural barriers usually associated with the conventional participatory methods. The applied e-participation process with its employed VR-ready models located within the initiated metaverse digital environment, allowed for an immersive and interactive experience that satisfactorily performed as a valid residents' engagement tool. It allowed participants to effortlessly understand the technical components of each alternative thermal retrofitting system and hence enabled them to compare and choose among them based on anticipated energy performance, capital cost, and preferred aesthetic considerations.

Table 8. Summary of results for the in-depth interviews of the e-participation sessions

No.	Gender	During the e-participation Selected alternative	Reason of selection	After the e-participation Capital cost influence	Potentials government incentives	E-participation experience
1	Females	Limestone tiles over rigid insulation	Beautiful option, less maintenance, durable against UAE weather	Cost was not a significant factor in her decision	Government incentives would encourage more people to adopt retrofitting strategies	Metaverse realistic and effective in understanding building details
2		Limestone tiles over rigid insulation	Durable, prevents energy penetration Emphasizes one-time cost benefit	Cost was considered but not a major deciding factor	Government incentives would encourage adoption of retrofitting strategies	Appreciated the realism of the metaverse but needed better resolution
3		Limestone tiles over rigid insulation	Aesthetic appeal, joint aesthetics	Cost was a consideration, but she preferred aesthetics as the main	Government assistance would encourage more adoption of retrofitting strategies	Metaverse is realistic and helpful in decision-making
4		Limestone tiles over rigid insulation	Classic appearance, protection from dust and rain, less maintenance	Cost was not a major concern due to the durability of her preferred option	Government support would encourage more adoption	The metaverse is realistic and valuable for decision-making
5		Self-insulated Aluminum panels	Dislikes lines Concerns about maintenance	Cost considered, but the durability and low maintenance of the stone are key factor	Government support is crucial; a higher subsidy percentage would garner more community support for retrofitting strategies	The metaverse offers a realistic experience, though I wish the resolution for villa details was better
6		Limestone tiles over rigid insulation	Protects villa from sun radiation, durable, and aesthetic	Cost is not a major concern due to the durability of the Limestone and its low maintenance requirements	Higher government subsidies would significantly sway community support towards retrofitting strategies	The immersive nature of the metaverse enhances understanding of locations and building details
7		Limestone tiles over rigid insulation	Natural, good ventilation, fresh air, and energy benefits	Cost is negligible due to the natural and health benefits of stone materials	Government should promote retrofitting for improved quality of life; incentives are crucial	Enjoyable experience in the metaverse

(*continued*)

Table 8. Continued

No.	Gender	During the e-participation Selected alternative	Reason of selection	After the e-participation Capital cost influence	Potentials government incentives	E-participation experience
8		Limestone tiles over rigid insulation	Aesthetic appeal, easy maintenance, and scenic views	Aesthetics matter, and the Limestone's appeal outweighs cost considerations	Subsidies are important; tailored to income levels, they could enhance community support	The metaverse offers better understanding of construction materials and processes
9		Stucco plaster over rigid insulation	Practical, simple. Simplicity in design is a priority	Cost is negligible for her	A 30% or more subsidies would increase community adoption of retrofitting strategies	The metaverse provides a superior understanding compared to images
10		Stucco plaster over rigid insulation	Cheaper, simple design. Prefers cost-effective options	Opted for Stucco plaster due to its affordability	Higher government support would boost community adoption	Positive but suggests improvement in navigation
11		Self-insulated Aluminum panels	Lightweight, unique design	Cost is paramount in selecting retrofitting strategies	Government encouragement is key	Enjoyable and detailed; caution for first-time users
12		Limestone tiles over rigid insulation	Aesthetic appeal and cultural preference. Prefers artificial stone if cost is an issue	Cost is considered; considers the less expensive artificial stone instead of natural stone	Higher government contributions could sway community support	Positive, finds 3D model realistic and clear
13		Limestone tiles over rigid insulation	Aesthetic appeal, ease of use, and suitability for villas	Cost is not a barrier; Awareness is needed for sustainability	Government support and community encouragement are vital	Metaverse offers clearer visualization than images
14		Limestone tiles over rigid insulation	Modern aesthetic and preference for simplicity	Cost is not a factor	Community may respond positively to government encouragement	Metaverse enhances understanding compared to images
15		Self-insulated Aluminum panels	Better shape, compatibility with classic villa styles	Cost significantly influences her selection	Government encouragement is crucial	Positive; metaverse aids understanding

(*continued*)

Table 8. Continued

No.	Gender	During the e-participation Selected alternative	Reason of selection	After the e-participation Capital cost influence	Potentials government incentives	E-participation experience
16	Males	Self-insulated Aluminum panels	Strong insulation, aesthetic enhancement	Cost significantly influences her selection	Municipality and community influence adoption	Metaverse aids understanding of concepts
17		Self-insulated Aluminum panels	Lightweight, heat-absorbing, and energy reduction	Cost is a determining factor	Higher government contributions would encourage support	Detailed layers aid understanding
18		Self-insulated Aluminum panels	Sleek appearance Cost-effective options	Cost greatly influences retrofitting system selection	Higher government funding could encourage adoption	Impressive and realistic; aids comprehension
19		Limestone tiles over rigid insulation	Durable, commonly used in modern villa designs	Cost is associated with the selected system's fixation	Government should promote strategy adoption	Metaverse offers superior visualization
20		Self-insulated Aluminum panels	Safe, environmentally friendly	Cost impacts retrofitting strategy implementation	Advocates for government loans to facilitate strategy implementation	Positive; finds metaverse visuals superior to images
21		Stucco plaster over rigid insulation	Cheapest option	Cost played a significant role, leading him to choose the cheapest	Government incentives would boost community adoption	Enjoyed the metaverse experience but noted issues with resolution

Source(s): Table created by authors

In their comments on the level of immersion, interactive experiences, spatial presence, and involvement, the interviewed residents mentioned that this e-participation process permitted them to visualize and explore retrofitting options in a 1:1 scale virtual interactive and immersive environment. Still, the feedback from the interviewed residents on the experienced realism of the explored alternative retrofitting systems in the metaverse varied.

Another evidence of the success of the explored e-participation process is the revealed interesting and somehow surprising responses towards their preferred retrofitting systems and the justification for these preferences that transcends the mere capital cost and energy savings of the retrofitting systems. After carefully explaining the technical specs, capital costs, and expected energy (electricity) savings for each of the three suggested alternative retrofitting systems to the interviewed residents and after they experienced each alternative in both detailed and overall formats through the metaverse virtual visits, their selected preferences and the mentioned justification of their preferences revealed that they gave more considerations to the most important aspects for them, apart from the mere capital cost consideration, such as durability, maintenance requirements, and visual appearance. The revealed preferences came different from the technically rational professional ones, as most of the participating residents expressed a preference for limestone tiles cladding as a retrofitting material, followed by the self-insulated Aluminum panels cladding, and the stucco plaster as the least preferred thermal retrofitting solution for them.

For those who selected limestone cladding, despite its higher capital cost, the justification was not only that it is more visually appealing but also that it is more durable compared to plastering. In addition, as the interviewed residents live in public housing dwellings that are usually externally finished with cement plastering and paint, they are very familiar with the durability problems of this finishing material such as visualized hair cracks, paint peeling, etc., besides its poor appearance compared to the limestone cladding. Also, from a socio-cultural perspective, one might notice that limestone cladding is commonly used as an external finishing material in *private* and more luxurious Emirati single-family housing, making it much favored over the cheap plastering material for residents of public housing. This is supported by the result that most of the respondents asked for financial support from the local authorities to cover the capital cost of this preferred limestone cladding retrofitting system. The reactions of the participants towards the potential governmental incentives for retrofitting their houses affirmed the essential role of such incentives in promoting sustainable housing practices and fostering community engagement in the thermal retrofitting process. Governmental support in the form of, for example, reducing energy consumption tariff for retrofitted houses, contributing to retrofitting materials cost, etc., can significantly encourage residents to take part in the thermal retrofitting of their houses especially for those who considered cost as a major factor in their decision-making. Such financial assistance from the government towards the capital cost of retrofitting systems is therefore considered a significant motivator for implementing sustainable retrofit solutions, indicating a positive correlation between policy support and community engagement in energy-efficient building practices.

On the other hand, the self-insulated Aluminum panels were not favored by the residents mainly because they were not convinced with it as a finishing material for their houses. They believed that it could be more suitable for public buildings rather than houses. Finally, Table 9 summarizes the applied phases of the explored holistic method and the key findings of each phase.

To maximize the impact of the findings, the following policy and practical recommendations are proposed. First, there is a pressing need for policy and regulation changes to support sustainable thermal retrofitting of the existing public housing stock in the UAE. One of the proposed changes is that the concerned local and public housing authorities introduce financial incentives, such as subsidies for thermal retrofitting costs or reduced electricity tariffs for retrofitted houses, to make thermal retrofitting more affordable to residents. Such incentives could significantly increase adoption rates of thermal retrofitting.

Table 9. Summary of the phases of the explored method in the study and the key findings of it

Phases of the explored method	Key findings
Phase 1 Selection of the components of alternative retrofitting systems	● Local construction market search led to defining three possible alternative retrofitting systems
Phase 2 Development of DT models of alternative retrofitting systems	● The local construction materials of the proposed alternative retrofitting systems were accurately represented in the three DT developed models
Phase 3 Energy Use Intensity (EUI) simulations	● The three proposed alternative retrofitting systems led to a sensible reduction in Energy Use Intensity (EUI) by a close value of about 30%
Phase 4 Capital cost of the alternative retrofitting systems	● Stucco plaster over rigid insulation emerged as the most cost-effective alternative, followed by self-insulated Aluminum panels cladding, while limestone tiles cladding over rigid insulation was the most expensive choice
Operational energy cost after thermal retrofitting	● Payback periods varied across retrofitting options, with stucco plaster then self-insulated Aluminum panels offering much shorter payback periods compared to the limestone tiles cladding
Phase 5 E-participation experience	● The metaverse immersive virtual environment was successfully initiated to include the base case before retrofitting besides the partial and full DT models of the alternative systems of the retrofitted house ● Limestone tiles cladding over rigid insulation was the most favored retrofitting systems for its durability, simple, maintenance, better social status expression and aesthetic appeal, followed by the self-insulated Aluminum panels cladding, and finally the stucco plaster over rigid insulation as least favored retrofitting system ● Participants appreciated the immersive experience of e-participation process in the metaverse as it helped them comprehend the technical aspects of the alternative retrofitting systems and hence in the selection of the most preferred one ● Government incentives were believed to play a significant role in motivating the adoption of selected retrofitting system(s), and in enhancing trust and credibility among participants

Source(s): Table created by authors

Moreover, mandating participatory decision-making processes in thermal retrofitting projects for public housing can ensure that residents' preferences and needs are genuinely considered, thereby improving the overall success of such initiatives. Training programs aimed at educating residents about the technical aspects of thermal retrofitting options for their houses and the expected economic and environmental benefits could further enhance their willingness to participate and invest in these projects.

6. Conclusions

Thermal retrofitting offers a viable and cost-effective solution for upgrading and improving the energy efficiency and sustainability of older houses. It is a less disruptive alternative to demolition, allowing homeowners to enhance the performance of their residences while preserving the sentimental value associated with their existing properties. It is claimed that such a process cannot be successful without genuine residents' involvement in the decision-making process of the definition of the applied thermal retrofitting techniques. Accordingly, this research delved into the pressing issue of enhancing the sustainability and energy efficiency of existing Emirati single-family public housing by proposing and exploring a five-phase local context-responsive and participatory thermal retrofitting method. This method integrates a professional definition of possible thermal retrofitting strategies, based on the local climatic and construction market, with the involvement of the residents in defining the most preferable retrofitting system for them through a proposed advanced e-participation process. Guided by 4 main questions, the exploration of this proposed method was performed through a multifaceted applied methodology including literature review, local construction market search, operational energy simulations, and in-depth structured interviews before and during the e-participation sessions conducted in an initiated immersive metaverse virtual environment.

To answer the first research question about the specifications, capital cost, and expected operational energy savings of the best locally available and applicable deep thermal retrofitting systems, that could sensibly reduce the operational energy consumption of the selected public housing model, a widely developed Emirati housing model was selected and three retrofitting systems involving a combination of conventional thermal cladding for external walls and roofs to reduce EUI were digitally developed as BIM models. These retrofitting systems included stucco plaster over rigid insulation, limestone tiles cladding over rigid insulation, and self-insulated Aluminum sandwich panels cladding, in addition to added roof insulation and window films in all systems. The EUI simulations of each of these three systems resulted in a predicted decrease of about 30% in the existing housing operational energy consumption.

To answer the research's second question about the main components and the operation method of the proposed e-participation process, the proposed e-participation process was successfully developed based on the utilization of advanced collaborative VR techniques in a specifically tailored metaverse digital environment to showcase the three alternative systems and their details for participants. These included advanced VR devices, metaverse collaborative applications, and a VR-ready powerful laptop.

As for the answer to the third research question about how satisfactory the outcomes of the e-participation process as a proposed efficient community engagement method in thermal retrofitting of existing public housing, this innovative e-participation process has effectively allowed for active engagement of residents in the decision-making processes related to the selection of the retrofitting strategies. Participants were able to understand how the retrofitting process would be implemented in their existing houses by virtually visiting the partially layered external walls and the fully developed DTs to examine scale 1:1 alternative systems and select what matches their preferences. Notably, most of the participants selected limestone tiles cladding as their most preferred retrofitting option based on durability, maintenance, appearance, and their background experience with it as a well-known reliable cladding system that needs minimum maintenance despite its high initial cost.

As for the last research question about the possible continuous utilization of the proposed integrated thermal retrofitting method that jointly utilizes both the locally responsive technical initiation of the alternative retrofitting systems and the proposed e-participation process for involving all stakeholders, especially the Emirati public housing residents and the federal/local housing authorities, the outcomes of the research revealed that meaningful reduction of the operational energy consumption of the existing housing, especially the energy consumed in meeting the high cooling loads due to the harsh climatic conditions in the UAE, could be achieved through appropriate passive thermal retrofitting of the envelops of these houses. In addition, by being involved in the proposed e-participation process, residents would be more willing to contribute to the initial cost and the maintenance of the retrofitting systems of their houses.

For this proposed method to be impactful the local housing authority should observe and assist in constructing the selected retrofitting system(s) in the existing houses, provide necessary support and guidance throughout the retrofitting process to ensure accurate implementation, collaborate with residents to monitor and evaluate the performance of the retrofitting systems over time, offer financial incentives or subsidies to encourage widespread adoption of sustainable thermal retrofitting practices among Emirati public housing residents, facilitate knowledge-sharing and capacity-building initiatives to empower residents with the skills and resources needed to maintain and manage their retrofitted houses effectively. They also need to foster ongoing communication and engagement between residents and relevant stakeholders to address any challenges or concerns that may arise during the retrofitting process. By establishing a continuous partnership between residents, local authorities, and other stakeholders, the widespread adoption of thermal retrofitting strategies in Emirati public housing can be promoted, leading to significant improvements in energy efficiency, sustainability, and overall quality of life for residents. As revealed in the research, when residents perceive that the government is actively promoting and incentivizing sustainable building practices, they are more likely to engage in such initiatives. This alignment between policy initiatives and community needs not only encourages participation but also instills confidence in the feasibility and effectiveness of retrofitting solutions.

On the other hand, the developed DTs of the houses would be useful for future implications in a continuous partnership process. If the concerned housing authorities decided to adopt the method applied in this research and after constructing the retrofitting systems in an existing house, heat transfer sensors could be added to the retrofitted house to digitally connect it to its DT through the Internet of Things technology. The collected data about the energy-related thermal performance of the retrofitted envelope of the existing house will be automatically analyzed and accordingly, the housing authority can discuss and agree with the residents about any possible required enhancement through the e-participation process in the metaverse.

The outcomes identify three important implications for research, practice, and society by demonstrating the feasibility of the proposed locally responsive and participatory thermal retrofitting method that aimed at enhancing energy efficiency in existing Emirati single-family public housing as has been successfully explored in this research where the outcomes have provided valuable insights into the effectiveness and implications of this proposed method with its e-participation process. The technology components of the explored e-participation process, such as BIM, DT, and VR modeling, and metaverse immersive virtual environment have been efficiently utilized to result in a genuine and innovative participatory decision-making process in housing thermal retrofitting. Accordingly, this applied method could contribute to the global efforts of community participation in housing design and decision-making (see for example McGill University, 2020). It efficiently underscores the importance of involving residents in the process by addressing their real needs and preferences in a way that contributes to sustainable housing solutions tailored to the community's requirements. With some residents asking for better resolution of the retrofitted models within the experienced metaverse virtual environment, it is expected that shortly, both the new versions of the VR hardware and the operating applications for the metaverse digital environments will be developed on multiple fronts including better realism through enhanced resolution.

In terms of practical application, the explored retrofitting local responsive and participatory method in this research is believed to be applicable in any other context with certainly different alternative retrofitting systems and would be responsive to each specific context. The participants expressed a strong desire for wider availability of this participatory technology, recognizing its potential to revolutionize design communication and to expedite participatory decision-making in retrofitting projects. Still, the process and the used tools are envisaged as valid regardless of the locality of the climatic conditions and construction market in each context. This reflects the scalability and generalizability of this method and its associated technical tools.

Furthermore, the research outcomes have the potential to influence public policy by promoting the integration of smart technologies in urban development and sustainability efforts. It could also be used in teaching and training programs to educate stakeholders about the benefits of thermal retrofitting and the role of advanced digital tools in facilitating such projects. The societal impact of the research outcomes appears in improving the quality of life and increasing resident ownership of retrofitting decisions. From an economic and commercial standpoint, the implementation of such a model can contribute to cost-effective, energy-efficient retrofitting solutions that improve the quality of life by reducing energy consumption and increasing environmental sustainability. The application of the proposed thermal retrofitting system would also add long-term economic benefits on multiple facets including, for example, the expected increased property value of the retrofitted house when it becomes an energy-efficient house (PlanRadar, 2023). Moreover, the thermally retrofitted house will yield a higher return on investment. Many local authorities would also offer incentives in various forms for the thermally retrofitted houses (Brough-Williams, 2025). In further research, the more elaborated economic feasibility of the proposed retrofitting systems, such as sensitivity analyses, would ensure that the capital retrofitting cost and the expected thermal retrofitting savings remain viable even with energy price instability.

Finally, the outcome of this study should be perceived within its defined limitations. It should be perceived that the predicted 30% reduction in EUI due to the assumed application of the retrofitting systems is based on simulation analysis results, which may not fully capture real-world conditions that could be investigated when practically applying the alternative thermal retrofitting systems on existing houses in further research. Also, while the study provides valuable insights with potential scalability, it is important to perceive its outcomes within the selected case study of a single public housing model. Future research should explore additional models to broaden the scope of applicability. In addition, the relatively small sample size of the 21 participants is another limitation. While being sufficient for reaching meaningful qualitative insights, a larger sample size would improve the statistical robustness of the findings and allow for a more comprehensive understanding of the preferences of involved residents. Also, in future research, alternative sampling techniques that aim to get a general sense of a larger group, such as simple random or stratified sampling, could be applied to enhance representativeness.

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