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Implement Virtual Reality, Digital Twin, and Artificial Intelligence in the Social Housing Renovation Project Based on the Blue Zones Concept

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Abstract: ‘Blue Zones’ is the region with the highest concentration and longevity of older adults globally, and the living environment there may provide some design inspiration to support healthy ageing. The main purpose of this study is to investigate stakeholders’ acceptance of the digital twin models based on the Blue Zones concept presented by virtual reality. The main participants were designers and clients involved in the renovation project of the Malvalaan community in the Netherlands. In our study, we identified clients’ requirements for housing renovation through interviews, established a digital twin model of the residential compound, and used AI-aided design to create healthy ageing scenarios. We used architectural drawings and virtual reality devices to show the environmental changes before and after the renovation. Although participants had different attitudes toward the Blue Zones concept, they preferred design schemes to be presented using virtual reality technologies. Future research is suggested to gain more insight into longevity regions and use the knowledge to create age-friendly environments for older adults.

Keywords: architectural design, virtual reality, digital twin, artificial intelligence, housing renovation

1. Introduction

The term ‘Blue Zones’ (BZs) originates from demographic research conducted nearly twenty years ago. It identifies regions worldwide where people live significantly longer. There are five BZs, including Sardinia (Italy), Okinawa (Japan), Nicoya Peninsula (Costa Rica), Ikaria (Greece), and Loma Linda (United States) (Bendjilali et al., 2014; Buettner & Skemp, 2016; Madrigal-Leer et al., 2020; Poulain et al., 2004, 2021; Willcox et al., 2006). The key characteristics of these regions, including strong community bonds, accessible and inclusive environments, and lifestyle patterns conducive to age well, provide valuable inspirations for renovation design, which offers new perspectives to designing environments that promote longevity and well-being (Marston et al., 2021). By applying the knowledge of BZs, the existing housing stock can evolve beyond mere architectural upgrades to become holistic living spaces supporting older adults’ physical, mental, and social health. For the neighbourhood scale, the current BZs could be the reference for transforming the community through environmental changes, bridging the connections between indoor spaces and nature, and fostering a sense of belonging among residents (Lakshmanan et al., 2020). All in all, BZs provide age-friendly features of the built environment that meet physical needs and nurture residents’ mental and social health.

The integration of advanced technologies such as virtual reality (VR) and digital twin (DT) with traditional architectural principles has been increasingly used in design studies and practices, particularly on urban and neighbourhood scales (Najafi et al., 2021). However, the advent of VR and DT presents a ground-breaking opportunity in architectural design. VR allows stakeholders and end-users (e.g. architects, engineers and decision-makers) to immerse themselves in the envisioned environment before construction begins, facilitating a deeper understanding and engagement with the proposed changes. This immersive experience could demonstrate spatial relationships, material finishes, and overall design aesthetics, facilitating more informed decision-making and client satisfaction (Koutsabasis et al., 2012). The technology application enables the collaboration between designers and clients, ensuring that the result aligns more closely with clients' needs and preferences. Current VR applications in architectural design have shown that VR can be utilised for many purposes, such as design evaluation (Koutsabasis et al., 2012; Ma et al., 2022). DT creates dynamic, real-time digital replicas of physical spaces. It can be used instrumentally in monitoring and analysing the performance of housing projects, allowing for continuous improvement and adaptation based on actual usage patterns and environmental factors (Yao et al., 2023). DT is often applied for building construction and maintenance with data exchange but rarely for design purposes. Artificial intelligence (AI) is increasingly used in architectural design to enhance efficiency, creativity, and sustainability (Bölek et al., 2023). AI tools can help architects generate multiple design options, 3D models, and renderings to create stunning visual effects and realistic simulations, potentially supercharging the design process and making it more efficient and collaborative.

With the development of VR, DT, and AI, architectural design approaches need to be changed in an efficient, scientific, and human-centred way (Vite et al., 2021). This study explores the innovative intersection of these technologies with the BZs concept in the context of social housing renovation projects. Although the process follows traditional architectural design steps: investigating user requirements, proposing design strategies according to requirements, 3D modelling, and final presentation to stakeholders, the innovation is how to apply these techniques to design, modelling, and presentation. The study will investigate the stakeholders' acceptance, especially the senior residents, of experiencing the renovation design based on the BZs concept using VR.

2. Methods

2.1 Research design

The study process is shown in Figure 1. The clients (senior residents) were involved in data collection and the VR experiment phases. In particular, the VR experiment focused on 'communication', which describes the exchange of information between participants experiencing the immersive environments in DT. The participants were: 1) five designers (one of them is a consultant from the housing association); 2) five clients (senior residents over 65 years old) willing to participate in the renovation design and use VR devices. They were invited to the study through an ethically approved recruitment process.

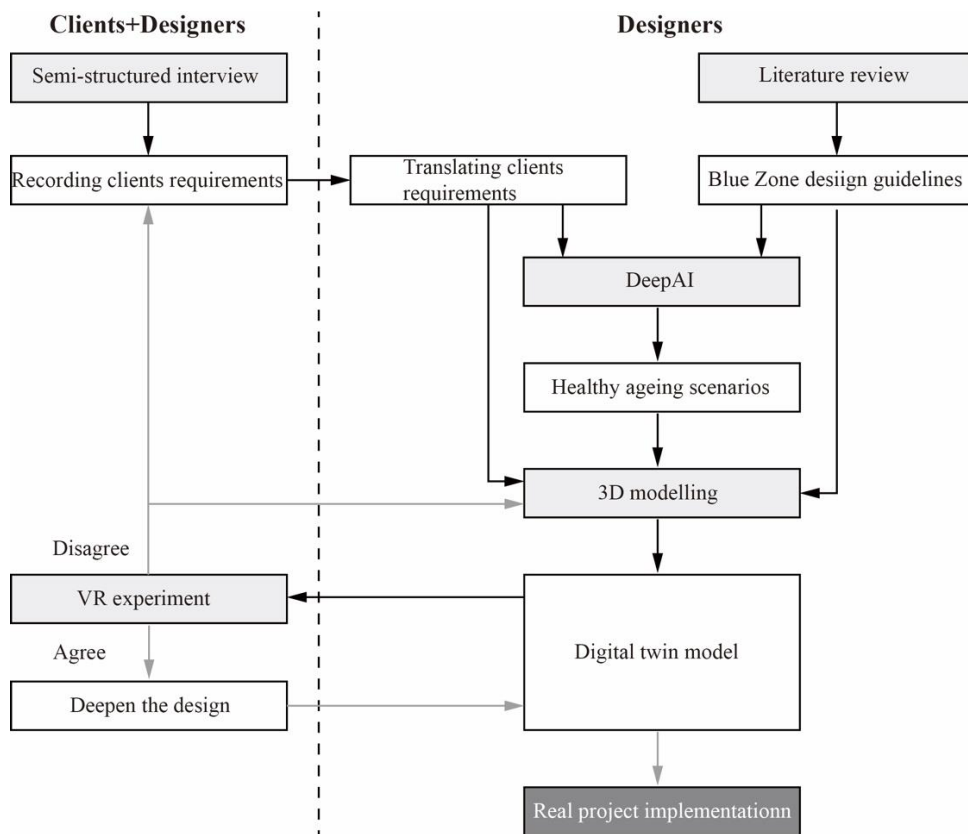


Figure 1. The workflow of the study.

2.2 Case study



Figure 2. The Malvalaan community before renovation.

The case study is in Malvalaan, the Netherlands. Currently, the community consists of three apartment buildings (Figure 2) where most residents live independently (One apartment building on the west side was demolished in 2021, and a new care centre is planned to be built on the same site). There are two apartment types for each floor (one living room and one bedroom for single persons; one living room and two bedrooms for couples), oriented east or west. The balcony of each apartment could be slightly different according to its

position (Figure 3). The apartment buildings were built in the 1970s and are connected by glass corridors. Although the outdoor common spaces are designed with barrier-free design guidelines and the greenery rate is high, the building facilities are still old, which influences residents' living qualities.

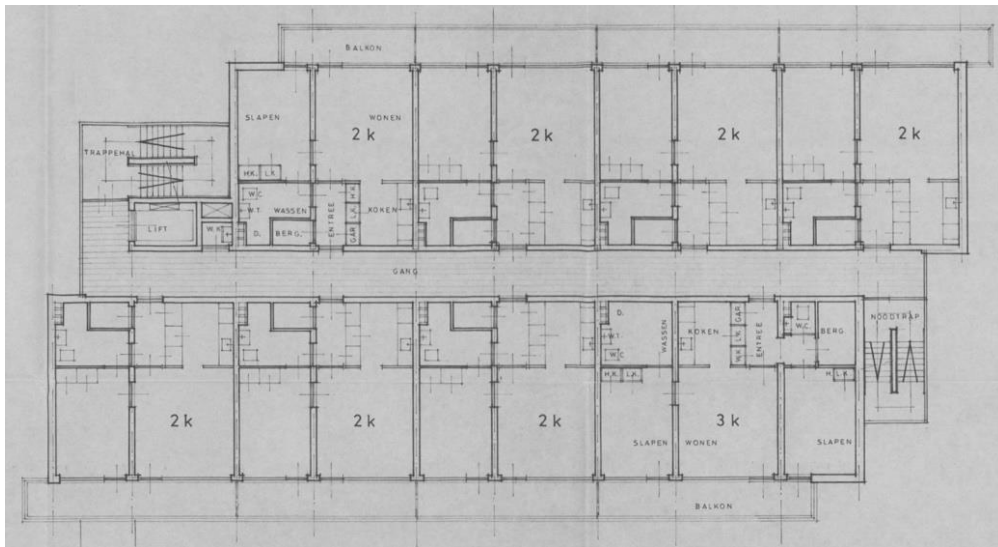


Figure 3. The floor plan of the apartment buildings (source: ARCHITEKTENBURO VAN DE KERKHOF).

2.3 Data collection and translation

The study started with a literature review and semi-structured interviews with five clients living in Malvalaan. Through the literature review, we searched the existing research focusing on the BZs concept at the architectural design level. The Keywords include: 'blue zone' and 'architecture' or 'building' or 'dwelling' and 'design' or 'guideline' or 'principle'. The knowledge of describing building characteristics and design features of BZs was screened and summarised.

Five clients, with an average age of 72.8, living in the studied community, participated in the research. They were invited to conduct semi-structured interviews in May 2023. During the interview, they described and showed their current living conditions, problems encountered, and the requirements for upcoming renovation from five main aspects: demographic information (e.g. how long do you live in Malvalaan), living environmental quality (e.g. how do you keep the natural ventilation in winter), daily activity (e.g. how you prepare a shower), space usage (e.g. how would like to change the room layout), and social connection (e.g. what do you do if in the emergency). The interview transcriptions were coded for thematic analysis, and each aspect was categorised by problems/hazards of the current living environment or expectations for renovation.

2.4 Scenario generation process

AI was employed in the renovation design process to conceptualise the BZs. We used pictures taken from interviews as base maps for AI generation. Detailed prompts based on the building characteristics and design features summarised from the literature review were employed in the AI image generator to produce images. Following the AI's generation of initial imagery, the images were then enhanced in Photoshop, adding more details and furniture. This was done to refine the visuals further and imbue the designs with greater depth and specificity to enhance the sensory perception of space through AI and human collaboration. The final designs emerged as a blend of AI application and human aesthetic judgment, intended to depict physical spaces and promote realism. This approach facilitates the rapid generation and testing of diverse design layouts and material choices, optimising the design process through efficient concept image generation. Due

to the limited documents, descriptions, and complexity of the BZs, AI tools were utilised to 'describe the living environments in BZs' based on big data to support the creation of 3D models.

2.5 Malvalaan DT modelling

We used three 3D and BIM modelling software platforms (SketchUp, Blender, and Revit). The model information and details were based on the architectural drawings from the architectural firm and photographic documentation of the sites. The three existing residential buildings, corridors, the community's landscaped features (e.g. slopes, pathways, trees, and benches), and adjacent streets were built according to the current situation. This virtual milieu was crafted to evoke a sense of familiarity amongst stakeholders. Emphasis was placed on accurately replicating the domiciles of clients, encompassing spatial configurations, furnishings, and textural details, to facilitate comparative evaluation. Renovation scenarios were created based on the current settings of each apartment, AI-generated images, and the specific requirements of each client. We also considered their health conditions, habits, and future lifestyles during the design phase. The VR animations were engineered using the Unity gaming engine, with the Meta Oculus Quest II envisioned as an interactive and customisable tool for urban and architectural exploration. Recent studies suggest that game engines, such as Unity and Unreal Engine, offer a heightened degree of interoperability in VR and provide cave automatic virtual environments with human-computer-interaction workflows, enabling the creation of interactive and immersive experiences. These engines also offer features such as real-time lighting and shadow effects, various camera angles and perspectives, and the ability to incorporate sound and other sensory elements (Deng et al., 2021; White et al., 2021). This model synchronises the environmental data (e.g. weather) with the outside world.

2.6 VR experiment



Figure 4. The participants in the VR experiment.

Five interviewed clients and five designers were invited to evaluate the proposed renovation designs. The VR experiment and data collection were conducted in the activity room in the Malvalaan community in December 2023. The researchers presented the renovation design concept to participants using architectural drawings and collected feedback on the BZs through questionnaires. Then, the participants were invited to use VR headsets to view the renovation design of selected scenarios (own home or others). The experiments for each participant took approximately 10 minutes, starting at the entrance of the building and ending at their apartments. Considering that the VR controllers could be complicated for older adults and the furniture in the room restricted the walking area, we designed a sitting mode for participants and helped them navigate the scenarios. We prepared a screen to show what people saw in VR headsets so all participants could freely share ideas and comments, such as which areas in the renovated rooms they liked or disliked. Subsequently, the qualitative data from these sessions were subjected to thematic analysis, a methodological approach to identify, analyse, and report patterns (themes) within the data. After using VR, they completed the questionnaires on VR experiences.

3. Results

A BZs checklist provided by (Marston et al., 2021) offers individuals a tool to understand their home environment and guidance for improvement. Based on the checklist and the interview transcriptions, Table 1 lists the feasible design strategies in each area: 1) Living room, 2) Kitchen, 4) Bedroom, and 4) Bathroom. Most checklist items are specific, such as 'place a longevity food list on the refrigerator' and 'use a walk-in shower stall', which can be used directly as a prompt for AI tools. The items, such as 'create a destination room/space for tranquillity and relaxation', need to take into account the daily life of older adults and the space usage to reword the prompt as 'wooden furniture in the living room is placed against the wall, only a wooden tea table and cushion are in the middle'.

Table 1. The description of the BZs interior design (selected for AI prompt) (Marston et al., 2021).

Living room	Kitchen	Bedroom	Bathroom
<ul style="list-style-type: none"> • Create a destination room/space for tranquillity and relaxation. • Design a clear space for exercising. • Decorate the room with plants. 	<ul style="list-style-type: none"> • Dedicate the top shelves with ornaments, plants, or food. • Add just the dining area and furniture for older adults. • Add design and detail that enhances appetite (e.g. a longevity food list on the refrigerator). 	<ul style="list-style-type: none"> • Use sun-shading elements on windows. • Design the bedroom with natural elements. • Improve the building insulation. • Install monitoring devices at the bedside. 	<ul style="list-style-type: none"> • Reinstall facilities and switches at proper heights. • Design a space for laundry. • Use a walk-in shower stall.

AI image generator (DeepAI) was used to generate the virtual rendering according to the BZs concept. Figure 5 is an example of images of reality (top), AI-generated (middle), and rendering in Unity Engine (bottom). The AI image was based on the prompts from Table 1 and pictures or descriptions of the Malvalaan residential buildings (e.g. 'Dutch old apartment', 'the balcony outside the living room', and 'wooden floor'). Although the AI images do not show the real scenes, they can be inspirations for designers who have not been to the BZs. Based on these images and the BIM model of the participants' apartments, we created renovated scenarios based on each room's layout, textures, furniture, and ornaments. The details referenced the AI images, such as the stickers on the fridge and room arrangements. Moreover, the 3D model layouts and textures, such as the TV set and furniture, were closer to reality. However, due to the hardware limitation and ensuring fluency in the VR environment, the rendering of model quality was not very high.



Figure 5. The picture was taken in the participant's home (top), AI-generated image (middle), and DT model (bottom).

VR technology lowered the threshold for participants to become engaged in the housing renovation design process, as no detailed technical knowledge is needed. Participants can discuss the scenarios, preferences, and problems when experiencing the immersive environment. The experiment provided clients access to what their homes will look like in the future, as the renovation can take years to complete. It allowed any complaints to be heard before the building began construction. Figure 6 shows the questionnaire results from the participants. They were asked to rate the design expression clarity, design process engagement, home environment improvement, renovation plan acceptance, and overall satisfaction with the design

presentation. Comparing the architectural drawings, the design expression clarity, process engagement, and overall satisfaction significantly increased using VR (red colour in Figure 6). According to the discussion, participants, especially the client, were quite surprised with the tailored interior design based on personal belongings. They said, ‘Yes, the furniture looks like my stuff’ and ‘That is understandable for me because the room is familiar and personal.’ They also discovered if some iconic objects were displayed somewhere in models. However, the participants still had different attitudes toward the renovated environments they saw in VR, and nearly half disagreed with some design concepts based on BZs. The clients care more about spatial usability and their own situations, such as the discussions during the experimentation, ‘I will never use the new destination room and do not think it helps keep longevity’, ‘I need storage space near the entrance’, and ‘I do not often cook, so I do not need a beautiful and greenery kitchen’. The designers also noticed the problems of space usefulness when they were in immersive environments and communicated with clients. This can provide designers with useful insight into the rationality of implementing design concepts in different regions and cultures.

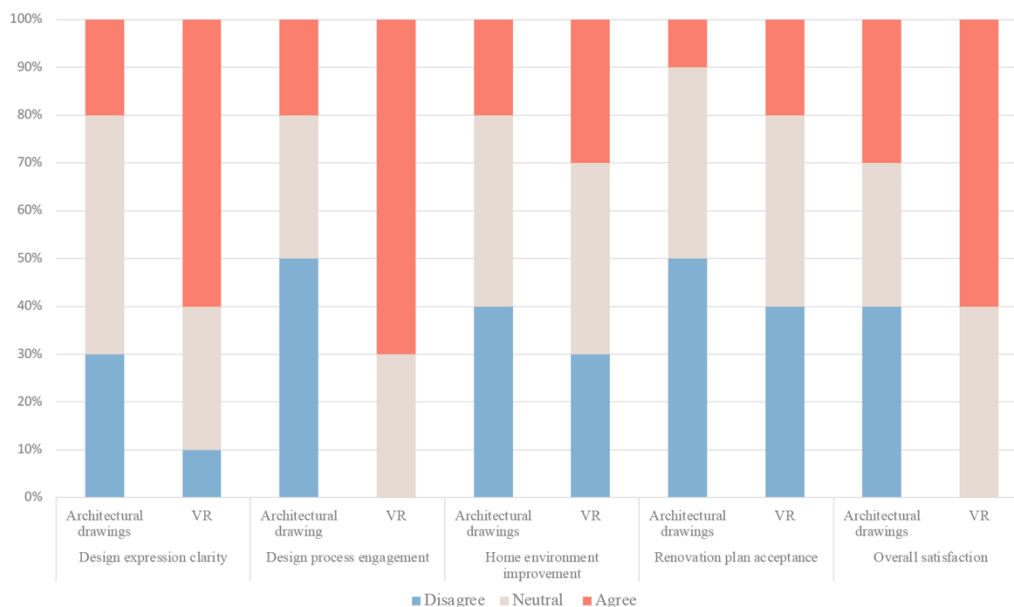


Figure 6. The questionnaire results of architectural drawings and VR presentation.

4. Discussion

This study explored implementing the BZs concept in the social housing renovation project using VR, DT, and AI. We developed customisable models for clients, which limited the number of participants in this research. Designers and clients reviewed and evaluated the renovation scenarios presented in immersive environments by VR devices. Considering that offering the conceptual design was the most critical phase of the design process, we used innovative methods to lower the threshold for older adults to participate in this phase (Cross, 2000). In this study, we found that the communication of the collaborative experiment process was interesting for all stakeholders and yielded constructive comments. Although there was a lack of statistical evidence, the VR experience was quite engaging and could be an effective tool in the experimentation for participants (Koutsabasis et al., 2012). AI adds value to architectural design and inspires. DT was indispensable for modelling and data interaction in the real and virtual worlds. These technologies present a meaningful, valuable, and affordable approach to co-create better age-friendly interior spaces for the studied community

(Mobach, 2008). Compared to architectural drawings, VR can help users gain a deeper understanding of the possible effects of renovation. Due to the existing literature providing limited descriptions of residential building characteristics of BZs, the output generated by AI tools and the BZs-based scenarios might not accurately present the improvement of living qualities after the renovation. Some guidelines, such as designing the room with natural elements, do not present the speciality of the BZs. Integrating indoor spaces and nature was beneficial to health, which has also been proved by different research fields (Zhong et al., 2022, 2023). Not all clients agreed with the BZs scenarios, but the actual demands they expressed, according to the VR experience, provided references and direction for designers to improve.

More theoretical underpinnings of the BZs research are needed to provide scientific guidelines for implementing healthy ageing practices. Given the healthy ageing narrative, the concept of incorporating a life course perspective for residents within the BZs who live in other countries is needed to fully gauge the factors of longevity (Editorial, 2007; Kreouzi et al., 2022). Additionally, due to the complexity of environmental effects on health and longevity, researchers and designers need to complement data, including indoor environmental parameters, building layout, and daily activity. Access to demographic information, physical ability, and other factors play essential roles in fully understanding one's personal and environmental circumstances. Thus, considering the variety of environments in which individuals live is critical for an inclusive approach (Marston et al., 2021). Exploring elements of healthy ageing from the BZs can assist their iterations and contribute to the ageing society.

5. Conclusion

In conclusion, integrating VR, DT, and AI in the design process, particularly within the social housing renovation project guided by the BZs concept, is a practical exploration. The synergy of these innovative technologies contributes to visualising the design concept and improving communications between clients and designers. The renovation scenarios were currently not well accepted because there was no adequate BZs knowledge to guide creating longevity environments. However, the immersive environments shaping 3D architectural spaces, components, and decorations offer more understandable effects than architectural drawings. This study underscores the importance of harmonising innovative technologies to provide more age-friendly design tools for the ageing population.

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