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Virtual Reality in Historic Urban District Renovation for Enhancing Social and Environmental Sustainability: A Case of Tangzixiang in Anhui

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Abstract: Virtual reality (VR) technology has attracted the attention of architectural practitioners due to its ability to allow people to interact with proposed design elements through unique and immersive experiences. This study aims at providing a bottom-up decision-making approach, using VR technology for inhabitant engagement in the design process of historic urban district renovation to preserve local culture, improve community interaction, and replace printed paper use for review. The study focuses on the Tangzixiang district in the Anhui province, providing Scheme 1 with a traditional architectural style and Scheme 2 with a modern architectural style for the renovation. The schemes are developed in a VR environment in both smooth movement mode and node-based movement mode. A total of 62 inhabitants and 10 architecture practitioners finished the VR experience, and the survey-based results indicate that VR quality can satisfy the requirements of practitioners in a professional review. In the inhabitants' view, Scheme 1, with a traditional architectural style, is identified as being more effective in preserving local culture. The scheme is improved by the design studio after the survey, based on the questionnaire results and comments. Notably, 56 participants scored five, indicating their agreement with the notion that VR enhances their engagement in the design stage. The effectiveness of the VR technology in the bottom-up decision-making process has proven to offer inhabitants opportunities to participate. This study demonstrates how this level of immersive experience in VR environments has the potential to be applied in more projects, aiding clients in better understanding design intent and helping them make more informed decisions early in the design process.

Keywords: virtual reality; historic urban district renovation; social sustainability; life cycle assessment

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1. Introduction

In China, the process of urbanization has led to an increasing focus on the renovation of historic urban districts among researchers, aiming to achieve sustainable development and economic growth concurrently [1]. To mitigate tensions between reconstruction efforts and cultural preservation, the government introduced the concept of "historical and cultural protection areas" in 1986, triggering widespread large-scale urban renovations in historic districts [2]. This study aims at providing a bottom-up decision-making approach, using VR technology for inhabitant engagement in the design process of historic urban district renovation to preserve local culture and improve community interaction.

Historic urban district renovation is necessary for solving conflicts between environmental conservation, cultural heritage preservation, and modernization [3]. In terms of social sustainability, renovation designs should incorporate the preservation of local cultural attributes and be guided by community input [4]. Public involvement fosters a transparent renovation process, fostering trust and garnering support from local residents [5]; however, public participation in renovations to promote social sustainability

always occurs prior to the design phase of renovations. To enhance the role of democracy in district renovation, we should find a mechanism that enables the inhabitants to participate in the planning and design of the renovation scheme or before construction.

VR has grown into an increasingly essential instrument in the field of architecture, allowing architects to convey their ideas to clients, stakeholders, and decision-makers in a more compelling and effective manner [6]. The implementation of visualization techniques has turned out to be essential in offering necessary information, particularly in fields requiring complicated processes for making decisions [7]. With its expanded usage across various domains, VR has become a critical aspect of decision support as well as optimization of design during the design process. In recent years, the integration of VR in the planning and design stage of building projects has gained popularity, revolutionizing the methodology of urban renewal and preservation. VR offers a unique and immersive experience for inhabitants to visualize and interact with proposed design elements [8]. Through VR, inhabitants can explore and interact with renovation plans in a virtual environment, allowing them to provide feedback and suggestions in real-time. This can help realize bottom-up decision-making throughout the renovation scheme, mitigate potential conflicts that may arise, and significantly enhance social sustainability in historic urban district renovations.

Another benefit of utilizing VR in the architecture design and planning process is the saving of printed paper in the scheme review. The printing industry has long been associated with high levels of pollution [9], and reducing the amount of paper used in construction projects can contribute to more sustainable practices. The government is encouraging paperless offices [10], but the review model for the architecture scheme in China still uses a large amount of printed paper for every reviewer. The VR can be a substitution for printed paper in showing the scheme details. Life cycle assessment (LCA) is a methodology that can assess the environmental benefits of printed paper saving; however, despite this, our current understanding of the extent to which environmental benefits can be achieved through the replacement of paper documents with VR remains limited.

Tangzixiang is a traditional street block that has been converted for cultural tourism and commerce while preserving the original layout of Wuhu's historic downtown. Chunliangli Street, the main internal street in the Tangzixiang area, is undergoing renovation. The reconstruction design of the Chunliangli historical street needs to respect the historical environment and improve the community environment quality to meet the needs of urban development. This study applies it as a case study in carrying out reconstruction design and virtual scene creation.

Herein, we aim at examining the potential of VR technology for boosting sustainability in the historic district renovation project. The technical feasibility of VR in Historic Urban District Renovation will be firstly investigated. For social sustainability, the effectiveness of the VR technology in the bottom-up decision-making process will be assessed to offer inhabitants opportunities to participate and promote both process and result democracy. For environmental sustainability, an LCA study will be conducted to figure out the environmental benefits of paper saving. The paper is organized as follows: In Section 2, a literature review on sustainable urban district renovation and the application of VR in architecture is provided. Section 3 introduces Tangzixiang in Wuhu as the renovation target and provides two renovation schemes. The construction of the VR scene, the survey and questionnaire for inhabitants and architecture practitioners, and the LCA methodology are provided in Section 4. The survey results and environmental benefits are analyzed in Section 5. Finally, discussions and limitations regarding the effectiveness of VR in the historical district renovation are provided in Section 6.

2. Theoretical Basis

In this section, the theoretical basis is summarized to provide a guide for the following survey. Research about sustainable urban district renovation is collected and summarized to identify the key factors for social sustainability in the district renovation. Moreover,

research about VR technology applied in urban district renovation is also summarized to support the VR scene construction in the following sections (Table S3).

2.1. Sustainable Urban District Renovation

Before designing the questionnaire, it is important to identify the key factors for social sustainability in the district renovation. The key factors can be the indicator or questions in the questionnaire.

One of the aims of the renovation projects is to enhance community welfare. This goal encompasses the provision of urban infrastructure and public services [11]. Urban renovation can provide an opportunity to prepare an infrastructure for community use, including open spaces [11], pedestrian walkways [12], housing, schools [13], care centers [14], and other amenities. Researchers carried out several studies on how infrastructure influences the social sustainability in the renovation projects. Lin et al. [15] shows that public amenities play a pivotal role in mitigating social inequality. Accessibility, denoting the availability of diverse facilities and services, represents fundamental support for residents. Enhancing the accessibility of essential life facilities relies on the presence of convenient, efficient, and secure sidewalks and transportation networks. Crucial services should be reachable within walking or cycling distance. Chan and Lee [11] listed urbanity, an appealing public realm, adequate housing, local environmental quality and amenities, accessibility, and walkable neighborhoods as physical factors. Additionally, health, quality of life, well-being, social inclusion, safety, mixed tenure, social cohesion, community, and belonging were identified as social factors. Wang et al. [13] showed that social facilities and commercial establishments, such as entertainment centers, cafes, and restaurants slated to open in the urban renewal area, will foster social cohesion, community spirit, and job opportunities. The provision of diverse social infrastructure and public facilities contributes significantly to social well-being, as it enhances public health and quality of life for various demographic groups, accommodates different modes of living, diminishes social inequality, and fosters civic pride [15].

Public engagement is one important aspect in district renovation for preserving social networks, enhancing citizens' sense of belonging, bolstering security against crime, and facilitating community participation in policy making [16]. Lin [15] proposed a decision-making framework based on the sustainability and urgency of urban renewal, presenting four dynamic implementation strategies tailored to various scenarios; however, a lack of evaluation of actual cases was noted. Certain studies have devised decision-making frameworks grounded in a limited-dimensional sustainability assessment framework [17]. Self-initiated and self-organized renovation is an important path for public-involved renovations in the future, which should able to preserve the local cultural identity and maintain a sense of place [18,19]. Yung et al. [18] conducted a survey of 312 people living in two urban renewal districts in Hong Kong using questionnaires. The results of the survey showed that self-organized renovation is significant for a community's sense of place, identity and development in the sustainable transformation of society. Zhang et al. [20] showed that most of communities received little support from national policy and local governance. Self-organized renovation is a key step to engaging neighborhood residents and fostering a bottoms-up approach into the planning and decision-making process.

Heritage protection is also a crucial factor i historic district renovation. Old buildings often become unsuitable for their original purpose due to deteriorating physical conditions and changing (as well as obsolete, economic, social, and environmental) attributes [2]. Langston et al. [21] made a project which cited Hong Kong as a case study of intensive city development. The study showed that it is important to be able to make quick judgements about existing built assets to identify and prioritize them for potential restoration activities. The building heritage protection is able to enhance the local social sustainability.

It can be also found that, as a bottom-up system, political sustainability requires community participation, which involves people living within the built environment, in making decisions regarding innovation. Furthermore, the degree of political sustainability

depends on the effectiveness and transparency of policies, and so citizen awareness of policy formulation and implementation plays a crucial role. Therefore, the attributes for socially sustainable renovation include facilities/social infrastructure, built environment, justice and equity, heritage protecting, cultural identity/sense of place, and public engagement/public participation (Table S1).

2.2. VR in Urban District Renovation

The development of VR technology has facilitated architectural design, review, and other related activities. Kodmany [22] is one of the first to incorporate urban simulations of the built environment into planning processes to engage the public more effectively. In recent years, some literature has focused on applying VR technology to urban district renovation.

Virtual environments offer several advantages for urban district renovation. Firstly, they provide a framework for integrating, modeling, and visualizing diverse layers of data, ranging from the simulation of human behavior to building energy demand, within the built environment [23]. Secondly, they enable stakeholders involved in planning processes to be situated within a common geographical frame of reference, facilitating access to information and familiar scenarios [24]. This accessibility benefits both participating experts and the wider public, allowing for the incorporation of social factors into decision-making processes [25,26]. Improving collaboration through VR technology can mitigate some of the common deficits associated with public participation in urban district renovation by promoting mutual communication [27]. Researchers have carried out several studies on how to apply VR in renovation projects. Meenar et al. [28] asserted that multisensory VR technology presents urban planners and policymakers with an opportunity to expand or complement traditional public engagement methods, while Adeel et al. [29] discerned the distinct attributes of the streetscape environment in the renovation project through VR. Findings revealed that, not only did road-related factors significantly influence people's preferences, but building heights were a major point of consideration as well. When strategizing and crafting urban design projects alongside mass transit initiatives, these noteworthy attributes merit consideration. Also, the movement mode in the virtual environment needs to be considered in the VR design [30–34].

The VR technology can be applied to different scales, including building scale, district scale, and city scale. It can help to improve environment management [23], human behavior [24,35], acoustic environment [27], visual environment [27,36–40], training and learning [41–44] in the design phase. The pathways for citizen participation include self-initiated participation, lead by the owner management committee, and questionnaires (Table S2).

2.3. Research Gap and Target

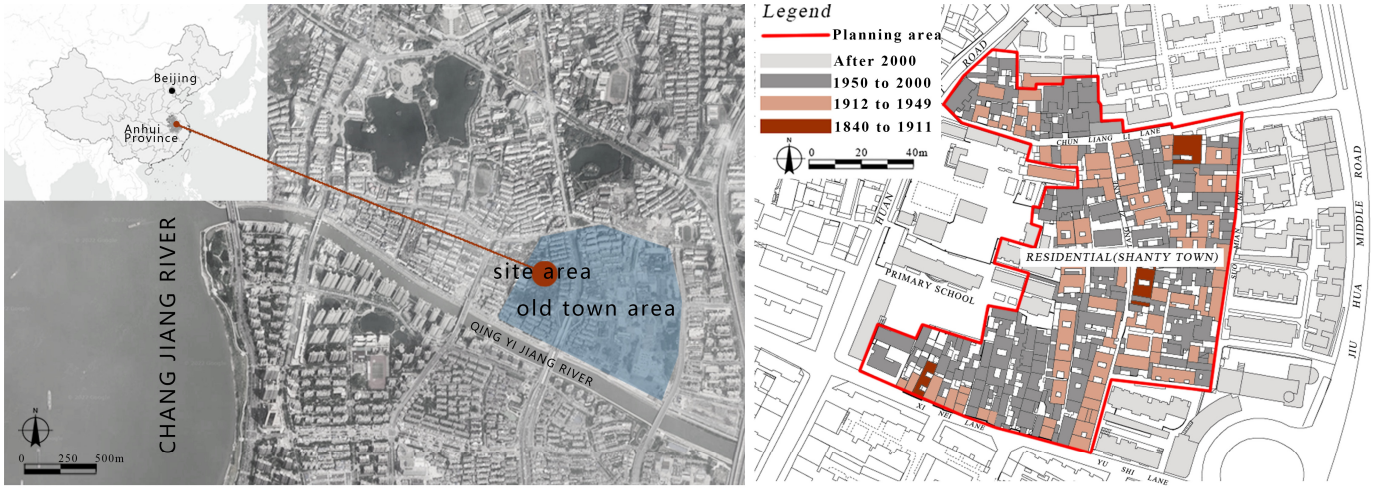
Although VR technology is widely used in the architecture field, so far no study has used it for public engagement as a decision-making approach in historical district renovation. Therefore, this study aims at providing a bottom-up decision-making approach that uses VR technology for inhabitant engagement in the design process of historic urban district renovation to preserve local culture, improve community interaction and replace printed paper use. Based on the literature review, a questionnaire is selected as the pathway for habitant participation. According to the attributes collected from the studies, the initial questionnaire is designed for the pilot survey.

3. Case Study

Tangzixiang in Wuhu City is selected as the renovation target. This section will introduce the facts and the renovation solutions of the case.

3.1. Facts of the Case of Tangzixiang

Wuhu City is an important port city in the middle and lower reaches of the Yangtze River in China. In 1876, according to the Sino–British Yantai Treaty, Wuhu was set as a trade port, becoming the only foreign trade port in the Anhui Province in the late Qing Dynasty. The famous Huizhou merchants went north to Wuhu through the Qingyi River and gradually established the most powerful commercial group. In the metropolitan region along the river, they, and merchants from all over the world, lived and constructed a huge number of dwellings and public structures. Tangzixiang is located in the west of the old city and is adjacent to the Qingyi River, a tributary of the Yangtze River, in the south (Figure 1a). Its planned land area is 3.11 hectares per square meter, which is a core historical section with priority development potential. During the Qing Dynasty and the Republic of China, celebrities and rich businessmen gathered here. The building age here ranged from 1880 to 2000 (Figure 1b). There are 14 historical protected buildings on the property, and the rest are shantytowns with poor environmental quality. The government is responsible for unified demolition due to the problems in safety, sanitation, comfort and privacy conditions. After the reconstruction, the infrastructure and environmental quality of the area will be greatly improved. In order to meet the community needs and induce urban development, cultural tourism and commercial functions will be added to the original residential functions.



(a) (b)

Figure 1. (**a**) Case location. (**b**) Planning scope and building construction period.

Tangzixiang is a traditional street block that has been converted for cultural tourism and commerce while preserving the original layout of Wuhu's historic downtown. The Jiuhua Middle Road on the east side of the block is the main road of the city and the most convenient road for the base's external traffic. On the east side of the road sits Wuhu Ancient Town, which is the main tourist and commercial block of the old city. Although the Tangzixiang Development Area is located in the core area of the main city, the architectural layout is irregular, and the internal roads are narrow, causing traffic inconvenience. Moreover, the internal community is old and the environmental quality is poor, which affects the tourism experience. In addition, the overall preservation quality of historical buildings is poor, and their style and appearance are disjointed. Former celebrity mansions from the Qing Dynasty and the Republic of China, as well as the Huizhou Commercial Hall, are among the 14 historical structures that must be maintained throughout the refurbishment. Most of them are single-story brick and wood structures, showing the characteristics of mixed styles and the styles of Huizhou in various historical periods (Figure 2). In 2021, the Wuhu government will renovate and protect the Tangzixiang District, which can attract more young consumers to make it a diversified place that integrates history, culture and local living environments. It is also linked with the business

district of Wuhu Ancient City on the east side of the urban road to drive the economic development of the old city. The history timeline of Tangzixiang is shown in Figure 3.

Figure 2. Preserved historical buildings and current street status. The 14 preserved buildings are marked in the figure.

In this paper, Chunliangli Street, the main internal street in the Tangzixiang area, is selected as the application scene to carry out reconstruction design and virtual scene creation. The reconstruction design of Chunliangli historical street needs to respect the historical environment and improve the community environment quality to meet the needs of the urban development. As the Tangzixiang area has a long history, for the historical buildings that have existed for nearly a hundred years, the missing architectural elements will be restored and regenerated according to the principle of identification to retain the authenticity of the historical buildings to the greatest extent. For the 14 historical protected buildings, on the basis of maintaining the authenticity of the facade style and architectural integrity, the main structure of the buildings shall be updated to ensure safety and efficiency in building use. For ordinary single buildings of poor quality, as their texture and composition characteristics add to the composition of the area, they are repeated, with few changes, to create the scale and style of the old street. The historical buildings in Chunliangli Street will be preserved as the cultural heritage of the historical landscape area in a longer and "healthy" way to achieve sustainable preservation and development of historical culture.

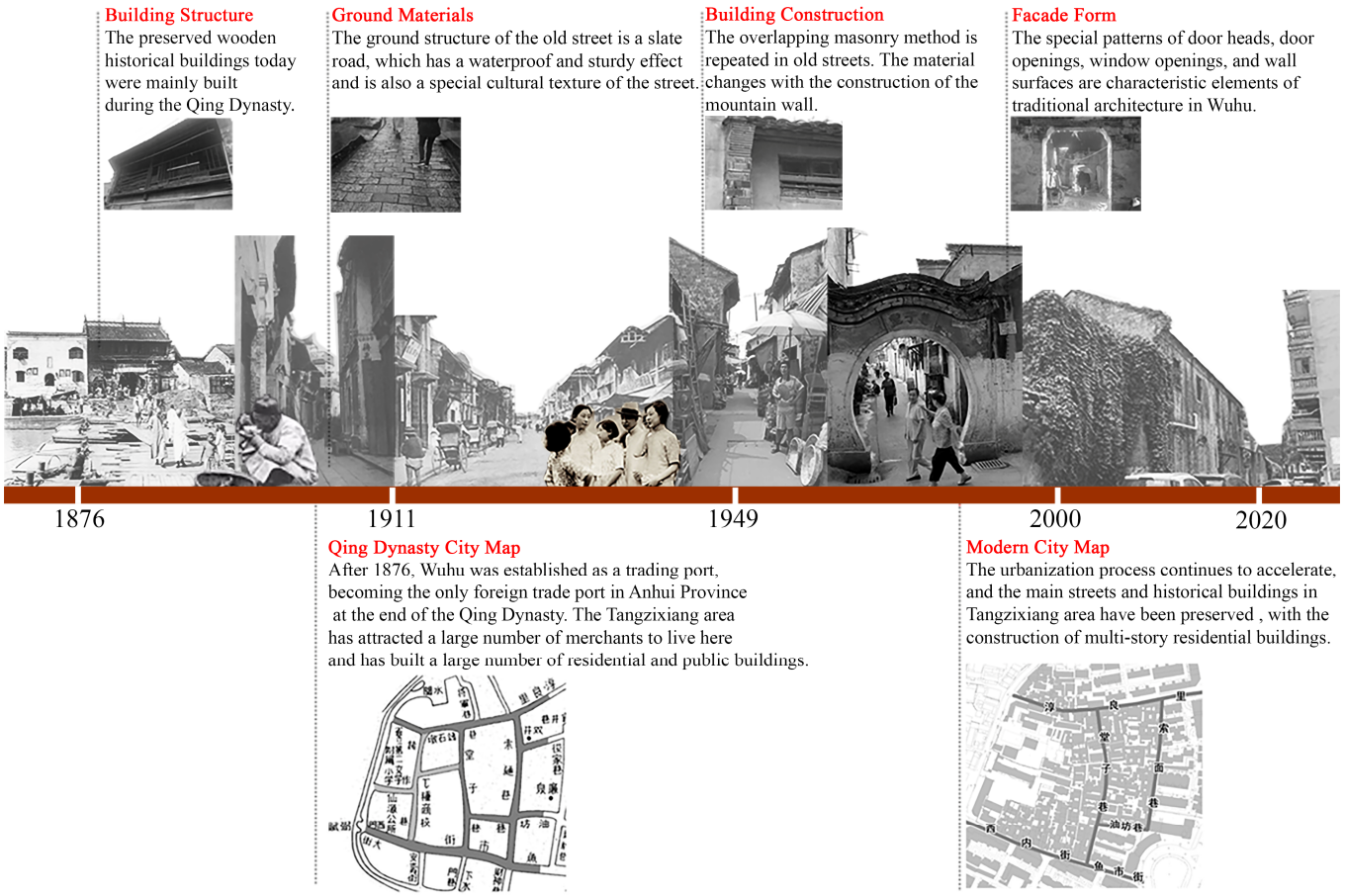


Figure 3. History of Tangzixiang.

3.2. Description of the Renovation Solutions

Scheme 1 is a traditional architectural style (Figure 4), which tends to focus on the protection of historical heritage. In this scheme, traditional architectural elements and the scale of street squares are inherited. The original inhabitants can obtain a sense of local dependence and identity through landscape perception, which has a positive effect on the sustainable development of social culture. The specific approach is to completely retain and repair five single historical buildings and one street doorway while retaining the sense of scale of the original street by controlling the street width, building height, public space, and greening. In terms of building material decoration, traditional materials, such as tiles, green bricks, and wood, are selected to retain the traditional texture of the original community.

In the design of new buildings, the traditional Huizhou architectural form and construction techniques are inherited. The architectural colors are mainly black, white, and gray. The typical fire sealing gable and carved windows of Anhui architecture are used. The roof form is a mostly sloping roof, and the local unique method of overlapping bricks on the wall head is also applied in some scenes. It continues and enriches the local attributes of the historical district, so that the original inhabitants can retain their original lifestyle and scene memories, promoting the sustainable development of community culture.

Scheme 2 is a modern architectural style (Figure 5), which tends to shape modern community public space and develop future cultural tourism functions. The sunken fountain square at the entrance of the historical block is a collecting and distributing communication space that adopts an asymmetric modern composition. The round door opening at the junction of the middle section of the street and Tangzixiang is the collective memory of the original inhabitants. The small round door at the entrance of the lane is reserved and developed into a small modern square. While evacuating the flow of people at the entrance of the lane, it serves as a close shared living room for the inhabitants of

the new and old communities to improve cultural sustainability. The modern style of new restaurants, shops, and hotels conforms to the aesthetic orientation of young tourists. Modern materials, such as concrete, glass, and steel, are used to attract more tourists and businesses. While enhancing the social inclusiveness of the community, they also bring about an increase in land value and rent, which is conducive to the economic sustainability of community development.

Figure 4. History of Tangzixiang.

Figure 5. Renovation Scheme 2.

4. Methodology

In this section, the construction of VR scene is shown. Then, the survey and questionnaire are presented.

4.1. Construction of VR Scene

To ensure a successful VR experience, the study employed both hardware and software. Specifically, the Oculus Quest 2 (developed by Reality Labs, bought in Wuhu, China) platform was utilized as the hardware component, consisting of a head-mounted display and a pair of hand-held controllers. This system allowed users to interact with the VR environment through the natural movements of their heads, bodies, and hands. For optimal immersion, a minimum unobstructed space of 2 m by 2 m was recommended for a room-scale setup. Rendering a VR environment is computationally intensive, and this study met the minimum requirements for providing a realistic VR quality. The survey conducted as part of this study was designed to assess the perceived realism of the current VR quality by the participants. The VR scenes are shown in Figure 6. The soundscape is collected in the surrounding environment of the district and added into the virtual environment.

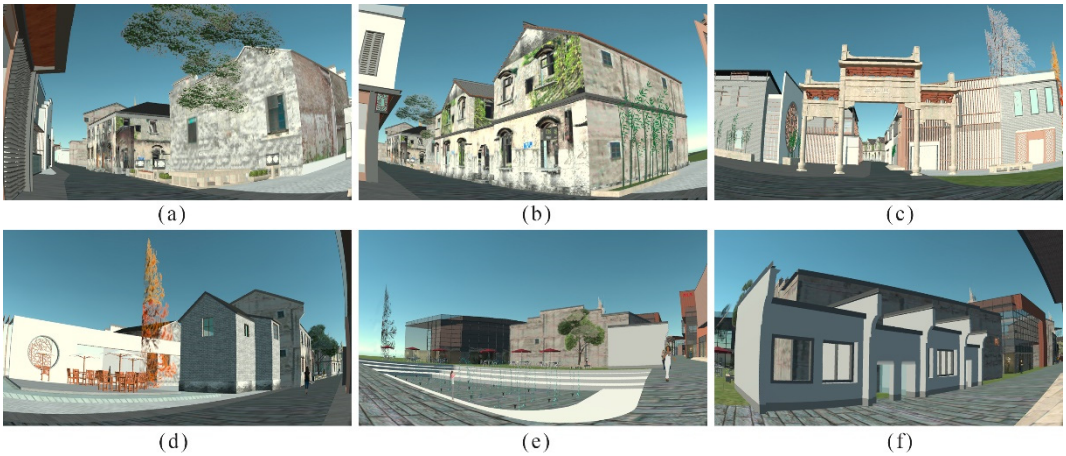


Figure 6. VR scenes. (**a**,**b**) Preserved historic buildings. (**c**) Entrance of the street in the Scheme 1. (**d**) The public space in the Scheme 2. (**e**) Sunken space in the Scheme 2. (**f**) Façade renovation in the Scheme 2.

This study employed Unity 6, which is capable of converting 3D models to VR. The import feature of Unity enables the conversion of .skp files, along with SketchUp Desktop 2019 layers and textures, into VR. The VR experience was designed to allow users to choose between two movement modes: smooth movement and node-based movement (Figure 7). The former mode, controlled by the joystick of the hand-held controllers, provided a more natural and seamless transition between locations. The latter mode involved players jumping to pre-determined locations. Both modes were available for selection at the beginning interface of the VR experience. The VR experience developed for this study enabled users to explore the renovated district and dive beneath its surface.

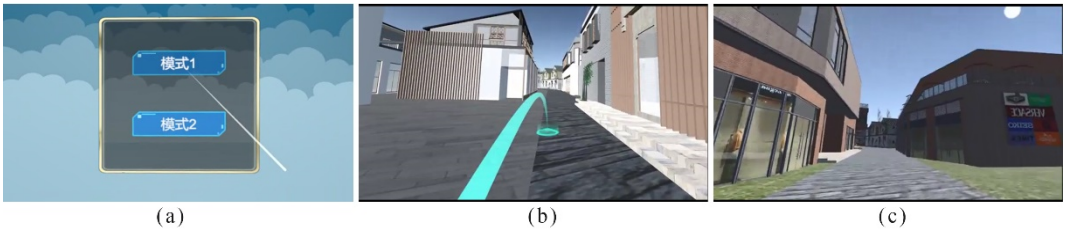


Figure 7. Movement modes in the VR scenes. (**a**) Choice of the movement modes. The characters are in Chinese for the inhabitants who are Chinese. It means Mode 1 and Mode 2. (**b**) Node-based movement. (**c**) Smooth movement.

4.2. Survey and Questionnaire

The survey is divided into two parts: one for the inhabitants to assess the effectiveness of the VR technology in the bottom-up decision-making process, and another for professional architecture practitioners, such as architects and public officials, to evaluate the use of VR devices in the scheme review as a substitute for paper materials.

Pilot survey: Before administering the official questionnaire, we conducted a pilot survey and short interviews with five inhabitants. The main aim of this pilot survey was to evaluate the questionnaire's appropriateness in terms of length, clarity of terminology and questions, and coverage of crucial factors. Based on the feedback received from the participants in the pilot survey, we made essential adjustments, such as reordering questions and refining those that were unclear.

Formal questionnaire: The formal questionnaire has 23 questions and is designed with four parts, including (1) personal data, (2) VR experience, (3) engagement of inhabitants, and (4) preservation of local culture. The participants' responses were evaluated using a scale consisting of five points (1: strongly disagree, 2 disagree, 3: neutral, 4: agree, 5: strongly agree). The questionnaire is shown in Table 1.

Table 1. Questionnaire.

Questions	No.	
Personal data:		
Gender		Male/Female
Age Group		<35/36–50/51–65/>65
Status of residence		Owner/Tenant
Hukou type		Local/Nonlocal
Duration of residence		<3/4–6/7–10/>10
Education		Lower than primary school/Elementary school/Secondary school/College or above
VR experience:		
Had you experienced VR before?	a1	Yes/no
Which movement mode do you prefer?	a2	Smooth movement/Node-based movement
I felt dizzy or sick.	a3	1–5
VR scene is realistic.	a4	1–5
I encourage the use of VR in renovation.	a5	1–5
Engagement of inhabitants:		
VR increases my engagement in renovation.	b1	1–5
VR increases democratic decision-making in renovation.	b2	1–5
VR improves self-initiated and self-organized renovation.	b3	1–5
Local culture sustainability on Scheme 1:		
The scheme avoids you losing the sense of place.	c1	1–5
The scheme improves community interaction.	c2	1–5
The scheme enhances city livability.	c3	1–5
The scheme preserves the local culture.	c4	1–5
Local culture sustainability on Scheme 2:		
The scheme avoids you losing the sense of place.	d1	1–5
The scheme improves community interaction.	d2	1–5
The scheme enhances city livability.	d3	1–5
The scheme preserves the local culture.	d4	1–5
What else you wish to add?		

Their personal data, including age, residence status (owner/tenant), Hukou type (local/non-local), duration of residence, and education level (lower than primary school/

elementary school/secondary school/college or above), were collected after obtaining their informed consent. Assessment of participant experience and feedback on the VR experience is essential to understand its potential for promotion. The questionnaire used in this study evaluates participants' preferences for the movement mode, the degree of discomfort, the realism of the VR, and their willingness to promote it. The study aims to enhance political sustainability in the historical district renovation. Based on the review in Section 2, the questionnaire includes questions on participants' engagement in the renovation scheme, democracy in renovation decision-making, and self-initiated/self-organized renovation. Additionally, the questionnaire investigates participants' views on the preservation of local culture under the two renovation schemes.

Participants: For the inhabitants in the renovation district, the study recruited 62 participants. All participants were informed that participation in the study was voluntary. Participants were recruited from diverse professions and backgrounds. The time to complete the VR operation and the questionnaire for participants were recorded. Survey scenes are shown in Figure 8. A prior training session on VR technology was conducted first to avoid confusion with the technology and the genuine motivation to participate in the decision-making process [45].

(a) (b) (c)

Figure 8. (**a**) Oculus VR device. (**b**,**c**) Participants in the VR experience.

Validity test: In assessing the suitability of item averaging, we employed Cronbach's alpha, a commonly used reliability metric. A Cronbach's alpha value surpassing 0.70 is traditionally indicative of scale reliability. Our findings, based on a sample size of 62, demonstrated a robust correlation among these items, with the Cronbach's alpha measuring at 0.823. This implies internal cohesion among elements, supporting their consolidation into a unified composite score.

For the architecture practitioners, we recruited 4 participants working in architecture design institute, 3 participants working in real estate companies, and 3 participants working in the government who are in charge of the renovation scheme review. They experienced the VR scenes and then finished a questionnaire, as shown in Table 2.

Table 2. Questionnaire 2 for architecture practitioners.

Questions	No.	
Personal data:		
Career		Design Institute/Real estate/government
Service year		<3/4–6/7–10/>10
VR experience:		
Had you experienced VR before?	e1	Yes/no
VR scene is realistic.	e2	1–5
I encourage the use of VR in scheme review.	e3	1–5
How much paper materials can be saved by VR?	e4	0%/25%/50%/75%/100%

4.3. Environmental Benefits from Paper Saving in China

Currently, the review of the renovation schemes in the design institutions and governments still utilizes paper material in China. A project undergoes multiple rounds of evaluation, necessitating the preparation of detailed design proposals for each expert involved. This process often results in substantial paper usage, which can have significant environmental consequences. The printing industry, in particular, is a notable contributor to environmental issues, representing one of the primary sources of stationary emissions of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) [46]. These emissions largely originate from the solvents used in printing inks and cleaning processes. The release of VOCs at such scales can have adverse effects on the environment, including the contribution to phenomena such as acid rain and ozone formation. Acid rain, for instance, poses threats to ecosystems as it infiltrates the soil, depleting essential nutrients and introducing harmful substances like aluminum into water bodies, rendering them toxic. Ground-level ozone, another byproduct of VOCs, presents health hazards and contributes to smog formation. Furthermore, improper disposal of VOCs and heavy metals, such as copper (Cu), in landfills can lead to soil and water pollution. Therefore, it is imperative to assess the environmental advantages associated with the adoption of virtual reality (VR) reviews as a potential replacement for traditional paper-based review processes.

In the survey for architecture practitioners, participants provide their opinions on the question "How much paper materials can be saved by VR?". To investigate the environmental benefits from the paper saving, a LCA is employed by the Simapro 9.3 and Ecoinvent database. For the life cycle inventory, the main materials used are "printing ink, offset, without solvent, in a 47.5% solution state [RoW]" and "paper and wood containing supercalendered [RoW]". For the process, printing one page takes 15 s with an ink-jet printer. The power of the printer is 750 W, and 500 mL printing ink can print 300 pages. In this project, we have provided six progress reports for the scheme review. Each report required the submission of seven books, with an average length of 82 pages per book. The cost for this renovation project is around 26 million yuan (3.7 million US dollar). Assuming that the amount of paper used is directly proportional to the project cost, this project represents the typical paper requirement for the scheme review process. In 2021, the construction scale of national construction projects reached 148.9 trillion yuan (21.0 trillion US dollar) [47]. Based on our assumption, the annual paper requirement for architecture scheme reviews in China is approximately 2.07 million tons. Recipe 2016 Midpoint H are used for the life cycle impact assessment. Given the environmental impacts mentioned in the last paragraph, the LCA results pay more attention to four indicators: ozone formation, fine particulate matter formation, mineral resource scarcity, and terrestrial acidification [46].

5. Results

5.1. Basic Information about the Participants

In March 2024, a questionnaire-based study was conducted in the Tangzixiang Historic District. Basic information about the participants was collected and arranged in Table 3. The ages of respondents varied, with three being below 35 years old, five being between 35 and 50 years old, seven between 51 and 65 years old, and eight being over 65 years old. The study found that the majority of respondents were retired middle-aged and elderly individuals who tended to stay at home during the day. Moreover, all 48 participants who owned their homes were found to be local residents. Additionally, most respondents had completed middle school or below, showing that education level influences the results.

Table 3. Participants' characteristics.

Questions	*N*	%
Age		
<35	8	12.9
35–50	12	19.4
51–65	19	30.6
>65	23	37.1
Status of resident		
Owner	48	77.4
Tenant	14	22.6
Hukou type		
Local	50	80.6
Nonlocal	12	19.4
Duration of residence		
1–3	9	14.5
4–6	8	12.9
7–10	9	14.5
>10	36	58.1
Education		
Lower than primary school	9	14.5
Elementary school	16	25.8
Secondary school	25	40.3
College or above	12	19.4

5.2. Time to Complete the Task

The efficiency of completing a VR operation and the questionnaire is a critical factor in the process of encouraging community residents to engage in the evaluation of renovation design schemes. Long operation times may negatively impact the willingness of community members to participate in such evaluations; therefore, investigating the factors that influence operation time is essential for developing effective and efficient VR-based interventions. In this study, we investigate the impact of age and education level on the time taken to complete a VR operation, with the goal being to identify potential barriers or facilitators to resident engagement in renovation design evaluations by VR technology.

The relationship between age and the time required to complete VR operations was analyzed and shown in Table 4. The relationship between age and the time required to complete the operation shows a statistically significant correlation (p-value 0.011) in the ANOVA analysis. For the 35 age group, an average of 15.9 min is required for the VR operation. For the 35–50 age group and 50–65 age group, 15.0 min and 14.5 min are required, respectively. However, the >65 age group only spent 9.8 min (standard deviation 1.1) on the operation, which is far shorter than other groups. The results show that age is an important factor which should be considered in the VR development of district renovation design.

Table 4. The relationship between age group and time taken to complete the task.

	Mean	Std. Deviation	Sig.
<35	15.9	3.4	
35–50	15.0	3.7	
51–65	14.5	2.8	
>65	9.8	1.1	
Total	13.3	3.7	
Between groups			0.011

One reason for the age-related differences in completion time is the level of interest or engagement with VR technology and the information presented in the questionnaire. Younger people and higher-educated people have more experience in using technology. They are more interested and motivated to explore the VR environment and to carefully

consider the questionnaire items, leading to longer completion times. In contrast, older participants and lower-educated participants are less familiar or comfortable with VR technology and may be more focused on completing the task rather than engaging with the VR environment. This can explain the shorter completion times observed in the >65 age group. Moreover, cognitive and physical changes that occur with aging should also be considered. As people age, they experience declines in cognitive and physical abilities that affect their ability to complete the task. Older participants have slower reaction times or experience difficulty navigating the virtual environment, and so they show a relatively negative attitude to operating VR devices, leading to shorter completion times.

5.3. VR Experience

The VR experiences of participants were surveyed in this study (Table 5). It should be noted that 19 of the participants had never used VR technology previously, with only a small number of young and middle-aged individuals (30.6%) reporting prior experience with VR. Regarding the operation methods of the VR system, 82.3% of participants preferred the smooth movement mode. This preference was based on the perceived reality of the mode, which was believed to be less likely to cause discomfort or dizziness. These findings highlight the importance of user consideration preferences and experiences in the design of VR-based interventions.

Table 5. VR experience.

Questions	N	%
Have you experienced VR before?		
Yes	19	30.6
No	43	69.4
Which move mode do you prefer?		
Smooth movement	51	82.3
Node-based movement	11	17.7

This study also investigated the relationship between age and self-reported sickness scores assigned by participants during the VR operation (Table 6). The *p*-value result, using ANOVA in SPSS, is 0.031. The relationship between age and self-reported sickness scores shows a significant correlation. For the under-35 age group, the mean score for "sickness" is the lowest, at 2.1. The >65 age group shows the highest score for "sickness", at 4.1, meaning that the VR scene is more likely to cause older people to feel sick, influencing their willingness to participate in the renovation scheme assessment.

Table 6. The relationship between age and VR sickness.

	Mean	Std. Deviation	Sig.
<35	2.1	0.7	
35–50	1.9	0.8	
51–65	2.3	0.8	
>65	4.1	1.0	
Total	2.5	0.9	
Between groups			0.031

In the present study, we surveyed participants regarding the perceived realism of the VR scenes utilized in the evaluation process (Table 7). Participants in the study expressed that VR technology offers legibility and realism. This finding highlights the benefits of using immersive technologies for design and planning to help residents understand the scheme. Therefore, VR technology is well-received by residents and holds promise in improving the evaluation of proposed renovation schemes. Compared to the opinions

of inhabitants in the "VR scene is realistic" and "I encourage the use of VR in scheme review", architecture practitioners gave relatively lower scores, with mean values of 4.2 and 4.2, respectively (Table 8); however, the results can still show the recognition and encouragement of architecture practitioners for the use of VR in the scheme review.

Table 7. Feedback on VR experience.

Questions	Mean	Std. Deviation
VR scene is realistic.	5.0	0.2
I encourage the use of VR in renovation.	4.6	0.3

Table 8. Feedback of architecture practitioners on VR experience.

Questions	Mean	Std. Deviation
VR scene is realistic.	4.2	0.7
I encourage the use of VR in renovation.	4.2	0.8

5.4. Engagement of Inhabitants

The findings from the questionnaire indicate that 58 of the participants scored five in response to the item "VR technology increases in your engagement renovation", showing that they perceive VR technology as being a useful tool for better engagement in the renovation project (Table 9). They expressed that it is particularly beneficial for residents in experiencing the scheme and thus helping them to give their suggestions. However, the participants scored 2.6 in response to the item "VR increases democratic decision-making in renovation", indicating a low level of interest in the final decision-making process of the community renovation program. They do not think they have a significant influence on the final scheme. The participants also scored 2.9 in response to the item "VR technology improves self-initiated and self-organized renovation", showing a lack of accurate knowledge on the matter. Participants attributed their responses to the fact that large-scale renovations like the one being undertaken are infrequent occurrences. Therefore, their responses were constrained by their limited exposure to the subject matter.

Table 9. Results about political sustainability in the questionnaire.

Questions	Mean	Std. Deviation
VR increases my engagement in renovation.	5.0	0.8
VR increases democratic decision-making in renovation.	2.6	0.9
VR improves self-initiated and self-organized renovation.	2.9	0.5

5.5. Preservation of Local Culture

To compare the effect of two renovation schemes on preservation of local culture, paired sample *t*-tests were conducted to examine the perceptions of the community residents (Table 10). The categories "The scheme improves community interaction" and "The scheme enhances city livability" yielded *p*-values of 0.13 and 0.71, respectively, indicating no significant differences in participants' responses. Conversely, results demonstrated that participants had significantly different views on "The scheme avoids you losing the sense of place" and "The scheme preserves the local culture", with Scheme 1 receiving higher ratings. These findings present Scheme 1 as being more effective in avoiding the loss of the sense of place and preserving local culture, according to the participants' perspectives.

Table 10. The difference of participants' views on Scheme 1 and Scheme 2.

Questions	Mean	Std. Deviation	t	Sig.
The scheme avoids you losing the sense of place.	−3.5	0.4	−40.0	<0.01
The scheme improves community interaction.	−0.6	0.5	−2.9	0.13
The scheme enhances city livability.	0.2	0.3	1.7	0.71
The scheme preserves the local culture.	−3.1	0.4	−40.0	<0.01

5.6. Feedback

In the polit survey, an open interview was conducted with the participants. Several respondents mentioned their focus on the public place.

"The fountain square is so good. I can take my son to play around. He can play with other kids. He must like it. I can chat with other parents". (Participant 13, female, 32, bachelor, local). This example demonstrates that a public area designed for children's play can enhance parent–child interaction as well.

Participant 19 initially visited the garden while experiencing the virtual environment and said, "I like to play poker. The garden is nice for us to play it in the warm days. And in the winter, we can move to the chessboard room" (Participant 19, male, 60, elementary school, local). His response indicates that public spaces for daily interaction are potentially the most important aspect for the participant. The garden and chessboard room emerge as two significant areas for elderly individuals.

"The chessboard room is still there. It is good! We (meaning the old people in the neighborhood) are used to go to there after dinner every day" (Participant 45, female, 52, elementary school, local). This illustrates that retaining the chessboard room is indeed a prudent decision for the renovation. These two instances underscore the importance of considering the daily activities of elderly individuals. Such considerations can greatly inform the design of public spaces during the design stage.

From the feedback, it can be found that public space is a key point to consider in the renovation plan, ranging from mobilizing community interaction to uniting society and forming cohesion, while even affecting daily political life. The public spaces in these two schemes have different perspectives in different age groups, and each person has their own preferences and concerns. In the eyes of young people, they prefer VR experiences that feature visual elements such as characters, fountains, and landscapes. In contrast, middle-aged people tend to prefer the appearance of public spaces, preferring street tours and architectural spaces. By comparison, the primary concern of elderly individuals lies in having access to areas where they can engage in recreational activities and maintain communication with others. The perception differences of public space related to age have a significant impact on the social sustainability of historical district renovation. Therefore, these findings confirm the potential benefits of integrating virtual reality technology and other innovative technologies into urban design to promote accessibility and inclusivity among different age groups. These technologies can promote immersive experiences and help bridge the gap between preferences of different age groups, ultimately contributing to the overall improvement of public spaces.

5.7. Environmental Benefits from Paper Saving in China

The survey results show that mean value of the amount of paper saved is 62.5%. Based on this value, an LCA study was conducted, and the results are shown in Table 11. Among the various LCIA categories, ozone formation, fine particulate matter formation, mineral resource scarcity, and terrestrial acidification are four of most essential impact indicators to normally assess the environmental impacts of the printing industry. From the results, it is apparent that substituting paper with VR for review can yield significant environmental benefits, with it being found that this practice can result in a reduction of 5.91×10^6 kg NOx

eq of ozone formation, 8.28×10^6 kg PM2.5 eq of fine particulate matter formation, and 9.77×10^6 kg SO_2 eq of terrestrial acidification. For mineral resource scarcity, 4.64×10^6 kg Cu eq can be saved.

Table 11. Environmental benefits in Recipe 2016 Midpoint H.

Impact Category	Unit	Total	Paper	Printing Ink	Electricity
Stratospheric ozone depletion	kg CFC11 eq	-1.01×10^3	-8.70×10^2	-1.35×10^2	-2.84
Ionizing radiation	kBq Co-60 eq	-1.05×10^8	-1.06×10^8	-1.37×10^6	-1.01×10^4
Ozone formation, Human health	kg NOx eq	-5.91×10^6	-5.78×10^6	-1.19×10^5	-9.73×10^3
Fine particulate matter formation	kg PM2.5 eq	-8.28×10^6	-8.15×10^6	-1.25×10^5	-2.81×10^3
Ozone formation, Terrestrial ecosystems	kg NOx eq	-6.01×10^6	-5.87×10^6	-1.26×10^5	-1.02×10^4
Terrestrial acidification	kg SO2 eq	-9.77×10^6	-9.57×10^6	-1.95×10^5	-8.04×10^3
Freshwater eutrophication	kg P eq	-2.66×10^6	-2.71×10^6	-4.55×10^4	-2.23×10^2
Marine eutrophication	kg N eq	-1.98×10^5	-1.69×10^5	-2.87×10^4	-2.66×10^1
Terrestrial ecotoxicity	kg 1,4-DCB	-6.27×10^9	-6.05×10^9	-2.11×10^8	-3.87×10^6
Freshwater ecotoxicity	kg 1,4-DCB	-9.32×10^7	-9.19×10^7	-1.32×10^6	-3.52×10^4
Marine ecotoxicity	kg 1,4-DCB	-1.26×10^8	-1.24×10^8	-1.81×10^6	-4.90×10^4
Human carcinogenic toxicity	kg 1,4-DCB	-1.29×10^8	-1.26×10^8	-3.28×10^6	-8.02×10^3
Human non-carcinogenic toxicity	kg 1,4-DCB	-3.70×10^9	-3.66×10^9	-4.42×10^7	-9.19×10^5
Land use	m2a crop eq	-1.42×10^9	-1.40×10^9	-1.46×10^7	-5.22×10^4
Mineral resource scarcity	kg Cu eq	-4.64×10^6	-4.57×10^6	-6.95×10^4	-2.63×10^3
Fossil resource scarcity	kg oil eq	-6.59×10^8	-6.29×10^8	-2.60×10^7	-4.09×10^6
Water consumption	m^3	-5.81×10^7	-5.74×10^7	-7.06×10^5	-1.90×10^4

6. Discussion and Conclusions

The objective of this study is to enhance the social and environmental sustainability in the historical urban district renovation by VR technology while providing a bottom-up approach in the scheme decision-making processes. The study was based on the district renovation of Tangzixiang in the Anhui province. Two renovation schemes were provided. According to the schemes, VR scenes were constructed with two movement modes. A survey featuring 23 inhabitants and 10 architecture practitioners was conducted. Participants were required to experience the schemes in the VR environment and finish the questionnaires. Based on the survey, the following conclusions cane be drawn:

(1) The effectiveness of the VR technology in the bottom-up decision-making process is proven to offer inhabitants opportunities to participate and promote both process and result democracy. An average score of 5.0 (out of 5.0) was given in the question "VR increases my engagement in renovation", indicating VR is able to improve the engagement of the inhabitants. Scheme 1, in a traditional architectural style, is more effective in avoiding the loss of the sense of place and preserving local culture. Public space was found as a key point to consider in the renovation plan, ranging from mobilizing community interaction to uniting society and forming cohesion, while even affecting daily political life. The scheme was then improved by the design studio after the survey based on the questionnaire results and comments.

(2) The average time required to complete the VR operation and questionnaire was found to be 13.3 min. As the age of participants increased, the time required to complete the task decreased. Conversely, an increase in educational level resulted in an increase in the time required to complete the task. The age-related and education-

related differences in completion time is the level of interest or engagement with VR technology and the information presented in the questionnaire.

(3) Smooth movement mode is preferred by participants. VR sickness is a challenge for the aged participants. Moreover, the VR quality is sufficient for effective scheme evaluation. VR technology is well-received by residents and holds promise for improving the evaluation of proposed renovation schemes.

(4) Using VR as a substitution of paper document for scheme review can achieve a reduction of 5.91×10^6 kg NOx eq of ozone formation, 8.28×10^6 kg PM2.5 eq of fine particulate matter formation, and 9.77×10^6 kg SO_2 eq of terrestrial acidification per year in China.

This study proves that VR surveys function as a tool for the evaluation of the quality of urban and building design, which is the same as the conclusions of previous researchers [7,43]. Furthermore, our study also indicates that VR surveys can play an important role in the decision-making process of design schemes to enhance public engagement. Therefore, in the evolving urban environments, VR surveys are poised to become indispensable tools for decision-making, offering a means to assess whether to preserve historical styles or embrace modern urban designs in transformed urban settings.

There are also some concerns from the results. In regard to community renovation plans, the questionnaires and interviews showed that, compared to the abstract and politically oriented sustainability measures, inhabitants are concerned more about the development of infrastructure and personal interests. Specifically, local participants show a high attention to government subsidies and other forms of financial welfare support. Another concern arises regarding Scheme 1, which features a traditional architectural style. In our study, we observed difficulties in distinguishing between historic and new buildings. To address this issue, we propose applying labels to the walls of historic buildings to provide information. There is a profound discussion on this topic in the heritage field that is worth addressing in the future.

This study also reveals a limitation, as the production process for the VR environment has proven to be labor-intensive and time-consuming. Enhancing the efficiency of VR production is necessary for the involvement of more professional VR engineers. Furthermore, the development of automatic programs and user-friendly interfaces can facilitate architects in navigating the VR production process more seamlessly. Only then can virtual reality reach its full potential as a research tool, providing numerous possibilities for environmental and behavioral research, such as highly accurate measurements, as well as exploration of systematic building variations in terms of post- and pre-occupancy evaluations.

For architects, this study can be a preliminary exploration to enhance social sustainability using VR in the architecture design and district planning. Although VR technology has several shortcomings (VR sickness, complicated production process), this study provides a process to improve public engagement with it, and, using the same method proposed in Section 4, other architects can copy the process and apply it to their projects.

Unlike previous studies, which focused more on the feasibility of VR technology in the building application, this study also assesses the effectiveness of VR on public engagement. In future work, the research will focus on extending the VR application in more building applications. More concern will be given to user and environmental characteristics, and eye-tracking will somehow replace the questionnaire as an alternative assessment method.

Overall, this study provides a bottom-up decision-making approach, utilizing VR technology for inhabitant engagement in the design process of historic urban district renovation. This study demonstrates that this level of immersive experience in VR environments has the potential to be applied to more projects, aiding clients in better understanding design intent and making more informed decisions early in the design process.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16072665/s1, Table S1: Attributes for socially sustainable renovation.; Table S2: Pathways for citizen participation; Table S3: VR technology applied in urban district renovation.

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