

Construction and Design of an Aging-in-Place Model for Residential Bathrooms Based on Digital Twin Technology- A Case Study of Bathroom Renovation for Elderly Individuals Living Alone in Beijing

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Abstract: *Amidst accelerating urbanization and intensifying population aging, the quality of life for mobility-impaired individuals and society's adaptive capacity to aging are directly influenced by the level of accessibility facility construction in homes. Currently, the home environment in China generally suffers from insufficient awareness and outdated facilities regarding accessibility, necessitating urgent improvement. This study focuses on the residences of elderly individuals living alone in Beijing and employs a combination of on-site surveys, questionnaire investigations, perceptual data acquisition, and Digital Twin technology. The methodology aims to precisely identify and quantitatively evaluate the domestic barrier-free environment. The findings provide a scientific basis for the age-friendly and disability-inclusive renovation of living spaces, holding significant practical implications for enhancing the convenience and safety of the elderly and mobility-impaired populations.*

Keywords: Virtual Reality Technology, Residential Space, Interaction Design, Aging-in-Place Design, Bathroom Design.

1. Introduction

As of the end of 2024, China's resident population aged 60 and above has reached 310 million, accounting for 22% of the total population. Within this group, the population aged 65 and above is 220 million, representing 15.6% [1]. This demographic trend signifies China's formal entry into a moderately aged society. With approximately 90% of the elderly opting for home-based care, the residential space is not only the core setting for their daily life but also the primary environment for rehabilitation and social activities. Therefore, the development of accessible environments in these spaces is crucial for ensuring the safety of the elderly and enhancing their quality of life and sense of well-being.

Currently, only about 12% of urban residences in China incorporate age-friendly design, with most living spaces exhibiting notable deficiencies in suitability for the elderly [2]. Common issues include excessively high thresholds, narrow passages, and inconvenient bathroom facilities. These inadequacies not only diminish the user experience but also escalate safety risks, such as falls. Consequently, the scientific rigor and rationality of residential space design directly impact the independence and safety of the elderly [3]. It has become imperative to integrate universal design principles into the entire process of housing construction and renovation.

Traditional design methodologies often suffer from standardization, low communication efficiency, and resource wastage. Precisely identifying user needs and ensuring efficient feedback mechanisms are key to design optimization. Recent advancements in new technologies, such as Artificial Intelligence (AI) and Big Data, offer novel support for accessible design in residential spaces. Virtual Reality (VR) technology, as an emerging interactive tool, provides an

innovative approach [5]. VR can simulate the real environment, enabling real-time interaction between the user, the environment, and objects. This allows users to participate in the design process, intuitively experience the renovation effect, and provide immediate feedback. Such engagement effectively prevents subsequent construction errors and resource waste, thereby significantly improving the scientific validity and practicality of the design.

In the pursuit of age-friendly and intelligent residential spaces, design principles should be optimized by integrating data analysis and interactive experiences tailored to the behavioral and psychological characteristics of the elderly. Comprehensive optimization of spatial layout, facility provision, and environmental atmosphere can enhance both safety and convenience while fostering a warm and pleasant living environment. The deep integration of accessible design principles with VR technology is thus not only relevant to the practical demands of an aging population but also crucial for promoting the intelligence, personalization, and inclusivity of residential spaces. This research holds significant theoretical and practical value for improving the quality of life for the elderly, optimizing elderly care models, and fostering inclusive societal development.

2. Current Status of Research on Residential Space Accessibility Construction

2.1 Current Status

2.1.1 Current Status of Residential Space Accessibility Design

With the continuous intensification of China's population

aging trend, the construction of age-friendly residential environments has increasingly become a focus of social concern. Data from the China Disease Surveillance System indicate that approximately 40 million elderly individuals experience at least one fall annually, with over 80% of these incidents occurring in the bathroom. This highlights the critical importance of age-friendly bathroom renovation for improving the elderly's quality of life and ensuring their personal safety, as the bathroom is the space most frequently used and harbors the highest concentration of safety hazards [4]. Beyond meeting safety and convenience requirements, bathroom design must also consider the privacy and independence of the elderly to maintain their dignity and sense of well-being [7].

Currently, preliminary progress has been made in age-friendly bathroom renovation in China, with some cities introducing barrier-free toilets, safety grab bars, anti-slip flooring, and emergency call systems in nursing homes and new residences [12]. For example, some Beijing households have experimented with "integrated barrier-free bathroom" designs, enhancing convenience and safety by widening doorways and installing sit-down shower areas and foldable shower seats. However, age-friendly renovation, overall, remains in the exploratory phase. Most families are limited by space and cost, resulting in localized micro-renovations, such as installing grab bars or anti-slip mats, which lack systematic and holistic planning, thus yielding limited results [6].

In general, accessibility renovations in Chinese residential spaces primarily consist of localized, functional improvements, lacking systematic and forward-looking planning. Practice suggests that design must incorporate the behavioral characteristics and psychological needs of the elderly from the initial stages, reinforce the concept of Universal Design, and promote the popularization and deepening of age-friendly renovation through policy guidance and standard refinement [9].

2.1.2 Current Status of VR Technology in Residential Space Accessibility Design

In recent years, Virtual Reality (VR) technology has been gradually introduced into the fields of architecture and interior design, with its advantages in immersive experience and visual representation offering new pathways and methods for age-friendly environment research. In China, the application of VR technology in age-friendly residential space design is still in the exploratory phase, mainly focusing on design visualization, interactive experience, and user demand simulation [10]. Designers can utilize VR technology to construct age-friendly scenarios in a virtual environment, allowing the elderly and their families to intuitively perceive the spatial layout and facility dimensions, thereby aiding design decisions and scheme optimization [11].

At the practical level, the design team for a renovation project in a Nanjing elderly care community used VR technology to build a virtual mock-up of the bathroom renovation. This allowed the elderly to wear VR equipment for an immersive experience, providing real-time feedback on the functional effect, thus enhancing the visibility and participation in the design process. However, the current application of VR

technology in age-friendly residential design in China is restricted by issues such as high cost, insufficient system integration, and low acceptance among the elderly, limiting its broader adoption.

In contrast, developed countries have established relatively mature application systems. Japanese research teams utilize VR to simulate reduced vision and slow gait in the elderly to optimize spatial dimensions and lighting design. European and American countries integrate VR with AI to develop personalized spatial experience systems, allowing users to provide real-time feedback in immersive environments, thereby advancing the humanization and refinement of design. Overall, VR technology offers new ideas for innovation in China's age-friendly residential environment, but its systematic application and widespread promotion require further development. Domestic and international practices show that VR technology can significantly enhance scheme validation and user participation in age-friendly design, but its effectiveness still depends on the refinement of software precision and interaction logic. Future efforts should focus on strengthening its synergistic application with technologies like BIM and AI and perfecting the experience feedback mechanism to achieve refined and intelligent accessible design.

2.2 Principles of Residential Space Accessibility Design

2.2.1 Safety and Comfort Principle

Safety is the paramount principle of age-friendly design and the core foundation for constructing an elderly-friendly living environment. Therefore, safety must always be prioritized in spatial planning, structural design, and material selection. Simultaneously, comfort is a crucial dimension for evaluating the quality of age-friendly spaces. Through the dual optimization of safety and comfort, a stable, warm, and psychologically secure living environment can be created for the elderly [8].

2.2.2 Economy and Practicality Principle

In the age-friendly renovation of residential spaces, economy and practicality are important design considerations. The concept of "economical and applicable, reasonable investment" should be adhered to, aiming to achieve maximized safety and convenience benefits within limited funding. By scientifically assessing the needs of the elderly and prioritizing the renovation of key functional areas and high-risk zones, the efficiency and practical value of the renovation can be significantly increased.

2.2.3 Person-Centered Principle

The fundamental starting point for age-friendly design lies in the authentic daily life needs of the elderly, and its core principle is "person-centered". The design must not only satisfy functionality but also maximize the assurance of the elderly's safety, autonomy, and dignity in daily life.

2.2.4 Case Study of Residential Space Accessibility Design Status

This research selects a family of elderly individuals living alone in Beijing as the case study, with two advanced-age residents. The unit is a three-bedroom, one-living room, two-bathroom apartment (Figure 1). The two bathrooms and their adjacent transition spaces are chosen as the primary research area, focusing on analyzing the current status of their accessible design, existing issues, and directions for optimization.

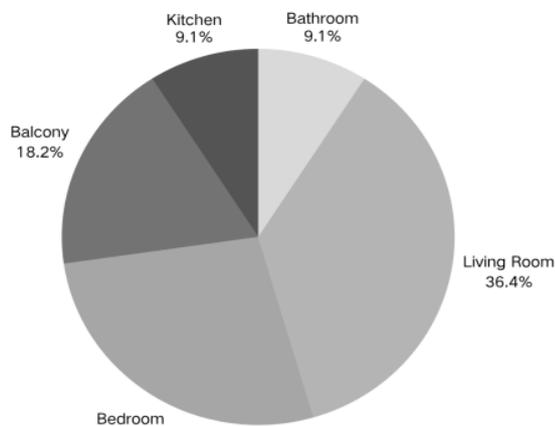


Figure 1: Functional Area Distribution Plan of the Case Study Residence

To accurately grasp the residents' living characteristics and spatial usage requirements, the study employs a mixed-method approach including questionnaire surveys, in-depth interviews, and on-site surveying. This systematic collection of key data—such as family structure, living patterns, self-care ability, current space condition, and renovation willingness—provides a scientific basis for subsequent design analysis and optimization.

During the design process, the study adheres to the principles of residential space accessibility and introduces Virtual Reality (VR) technology to optimize the design flow and presentation. Through immersive VR simulation and interactive experience, designers and users can validate the scheme's rationality from multiple perspectives. Based on this, and combined with the physiological characteristics and psychological needs of the elderly, targeted strategies for spatial optimization and accessible renovation are proposed. The goal is to construct a safe, convenient, comfortable, and adaptable living environment.

3. Living Patterns

The case study focuses on a typical household of two advanced-age residents, representing a classic "one-generation living" pattern of long-term independent residency. Although their children work and live in the same city, the considerable distance between residences makes it difficult for family members to arrive promptly and provide

effective assistance during emergencies, posing a definite safety risk. From the perspective of family structure, both children face heavy work pressure, making continuous daily caregiving challenging. Grandchildren only visit occasionally on weekends or holidays due to their academic commitments, further highlighting the limitations of external support. Both elderly residents exhibit a high degree of independent living ability; their daily routines (meals, self-care, and recreational activities) are primarily self-managed, their pace of life is regular, and their social circle is relatively limited.

Given the co-existence of high self-reliance and high emergency vulnerability in this independent living model, the focus of the spatial intervention in this research is clearly defined: while ensuring the independent living and residential safety of the elderly residents, priority must be given to optimizing the convenience of emergency response and the comfort of daily activities.

3.1 Self-Care Ability

In this case, both advanced-age residents belong to the over-75 age group, a sensitive phase where physical functions are rapidly declining. To scientifically guide the age-friendly design, this study conducted a systematic assessment of their physical function and self-care level using interview methods combined with the Activities of Daily Living (ADL) and Instrumental Activities of Daily Living (IADL) assessment scales.

In terms of health status, both residents show typical aging symptoms such as osteoporosis, visual impairment, and hearing loss, yet their overall health level can still support basic daily activities. The assessment results for ADL and IADL indicate that the residents are generally at a mild dependency level for daily self-care, with scores of 24 and 20 respectively, placing them in the higher range of mild dependency. However, they experience significant difficulty in activities requiring balance and major movements, such as standing up, squatting, and climbing stairs, which falls into the moderate dependency category. Furthermore, interviews revealed that the male resident requires a standard cane for balance, further suggesting a potential risk of falling.

In summary, considering the advanced age, declining self-care ability, and potential balance risks of the elderly residents, the subsequent accessible design for the residential space must center on the core principles of safety and practicality. The design needs to highly prioritize convenience and adjustability, structurally and spatially reserving appropriate conditions for future modifications, such as the use of a wheelchair or more advanced assistive devices, thereby achieving continuous adaptability and sustainable optimization of the living environment.

Table 1: Family Member Composition (Source: Self-drawn)

Family Member	Age	Occupation	Physical	Hobbies	Notes
Elderly Female Resident	76	Retired Worker	Mild Disability	Watching TV, taking walks, reading	\
Elderly Male Resident	78	Retired Worker	Mild Disability	Watching TV, taking walks, reading	\
Son	48	Office Worker	Healthy	\	Living Separately
Daughter-in-law	47	Office Worker	Healthy	\	Living Separately
Granddaughter	21	Student	Healthy	\	Living Separately

3.2 Current Spatial Status

The case study residence is located on the 10th floor of a high-rise building in Beijing, featuring a reinforced concrete structure and an elevator, which essentially meets vertical transportation needs. Through on-site investigation and in-depth interviews, the research identified the two bathrooms

and their adjacent transition spaces as the critical vulnerability areas impacting the daily convenience and safety of the two residents. Therefore, these two bathrooms, which differ in function and usage frequency, along with their adjacent transition spaces, are selected as the focus of the study for targeted age-friendly renovation design. The current spatial status and survey results are detailed in Table 2 and 3.

Table 2: Existing Status of Spatial Components (Source: Self-drawn)

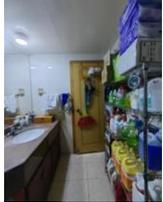
Functional Space	Dimensions (mm)	Orientation	Furniture	On-site Photo
Bathroom Adjacent to Kitchen	2100*3300	Northwest	Toilet	
			Shower Head	
			Sink	
Adjacent Transition Space (Kitchen)	1100*2060	Northwest	Washing Machine	
Master Bedroom En-Suite Bathroom	2260*835	North	Toilet	
			Bathtub	
			Sink	
			DIY Storage Rack	
Adjacent Transition Space (Master Bedroom)	4460*3420	North	Dining Table	

Table 3: Existing Status of Spatial Materials (Source: Self-drawn)

Functional Space	Door(mm)	Wall Surface	Ceiling	Floor Material
Bathroom Adjacent to Kitchen	770*2000 Wooden door (protruding round handle)	Tile	PVC Panel	Tile
Adjacent Transition Space (Kitchen)	\	\	\	Marble
Master Bedroom En-Suite Bathroom	800*2000 Wooden door (protruding round handle)	Tile	PVC Panel	Tile
Adjacent Transition Space (Master Bedroom)	800*2100 Wooden door (protruding round handle)	\	\	Wooden Board

3.3 Usage Conditions

The residence includes two bathrooms, located next to the kitchen and inside the master bedroom, respectively. Both are enclosed spaces primarily reliant on artificial lighting systems, representing a shared environmental defect.

1) Bathroom next to the Kitchen

This bathroom is situated on the northwest side of the residence, with plan dimensions of approximately 2100mm × 3300mm. The layout is compact, equipped with a toilet, shower, sink, and shelves. As the main daily hygiene space for both residents, it is used frequently. Due to a lack of effective ventilation and natural light, the space is prone to high humidity, and the drainage system often accumulates water, significantly increasing the potential risk of slips and falls on the wet floor.

2) Bathroom inside the Master Bedroom

This bathroom is located on the north side of the residence,

with plan dimensions of approximately 2260mm × 3835mm, and a relatively complete functional configuration (toilet, bathtub, sink, shelves). It is primarily used for nighttime toileting and washing, with infrequent use of the showering function. The main safety hazard is the excessive height of the bathtub, which poses an extremely high risk of falls for the elderly when entering or exiting.

Both bathrooms share common issues such as insufficient illumination, poor ventilation, unclear definition of wet and dry areas, and inadequate storage space. The shortage of storage leading to clutter further restricts movement space and exacerbates safety hazards. While the residential bathrooms fulfill basic functions, they exhibit significant shortcomings in accessibility, safety, and convenience. This paper will integrate Digital Twin and accessible design principles to systematically optimize and renovate the functional layout, facility configuration, and safety details of the toilet area, sink area, shower area, and their adjacent transition spaces. Detailed usage conditions and survey data are presented in Table 4.

Table 4: Bathroom Usage Status (Source: Self-drawn)

Functional Space	Behavior	Specific Actions Performed	Assistive Needs
Bathroom Adjacent to Kitchen	Toileting, Washing, Showering, Cleaning	Bending, Half-squatting, Standing, Sitting	Assistance to Stand Up
Master Bedroom En-Suite Bathroom	Toileting, Washing, Cleaning	Bending, Half-squatting, Standing, Sitting	Assistance to Stand Up
Figure Description			
Existing Floor Plan of the Bathroom Adjacent to the Kitchen			
		<p>1. Lack of grab bar at the sink area 2. Lack of dedicated storage space 3. Insufficient space for wheelchair access</p> <p>1. Lack of grab bar at the toilet 2. Insufficient lateral clearance</p>	
Existing Floor Plan of the Master En-Suite Bathroom			
		<p>1. Lack of grab bar(s) at the toilet 2. Insufficient lateral clearance</p> <p>1. Lack of grab bar at the bathtub 2. Lack of storage space</p> <p>1. Lack of grab bar at the vanity 2. Lack of dedicated storage space 3. Insufficient space for wheelchair maneuverability</p>	
Bathroom Adjacent to Kitchen		Master Bedroom En-Suite Bathroom	
Existing Spatial Issues Identified via Survey and Interview	<p>1. Toilet Area The toilet is too close to the side wall, inconvenient for elderly users. Toilet paper holder is missing, temporarily placed next to the sink. There is a noticeable height difference (threshold) at the floor drain area.</p> <p>2. Shower Area The floor is slippery, prone to falls. Lack of grab bars; the elderly need to lean on the wall for support during showering. Lack of a shower chair; the elderly sit on the toilet for rest while showering. The shower head is too close to the side wall. No low-level shower head holder is installed.</p> <p>3. Vanity Area Insufficient clearance space beneath the vanity, preventing seated grooming. The vanity is too close to the side wall, restricting the elderly's arm movement during use. Too few power outlets to meet the needs of the elderly.</p> <p>4. Storage Area Limited storage space in the bathroom.</p> <p>5. Circulation Area The bathroom space is large but poorly laid out, lacking sufficient maneuvering space for a wheelchair.</p>	<p>1. Toilet Area The toilet is too close to the side wall, inconvenient for elderly users. Toilet paper holder is missing; temporarily placed next to the sink. There is a noticeable height difference (threshold) at the floor drain area.</p> <p>2. Shower Area The floor is slippery, prone to falls. Lack of grab bars; the elderly are afraid to use the facility (bathtub).</p> <p>3. Vanity Area Insufficient clearance space beneath the vanity, preventing seated washing. The vanity is too close to the side wall, restricting the elderly's arm movement during use. Too few power outlets to meet the needs of the elderly.</p> <p>4. Storage Area The self-made storage space behind the door conflicts with the door's opening direction. Limited storage area.</p> <p>5. Circulation Area The bathroom space is large but poorly laid out, lacking sufficient maneuvering space for a wheelchair.</p>	

4. Residential Space Accessibility Design

4.1 Bathroom Accessible Design

The core of this age-friendly renovation is functional reconstruction and latent adaptability. Addressing the issues of ample original spatial dimensions but irrational layout, and

ambiguous functional zoning leading to limited effective usable area and spatial waste, the design systematically optimizes the overall layout based on accessibility principles. Specific measures include strategically adjusting the spatial organization of the toileting area, showering area, sink area, and storage area. By redesigning the circulation flow and partitioning interfaces, the smoothness of daily movement paths is significantly improved, and the risks associated with turning and stepping for advanced-age users are effectively reduced.

The design integrates the original temporary storage facilities into the overall system, reasonably consolidating storage space to ensure a compact and orderly layout. Concurrently, the design fully considers the dynamic changes in the physical function of the elderly and future long-term needs. Space is reserved for caregiver activities and the installation of auxiliary facilities, thereby achieving the latent design objective of “currently suitable—future expandable”. This reconstruction not only optimizes the functional layout of the bathroom but also lays a solid foundation for subsequent in-depth age-friendly detail design. The specific spatial layouts and dimensions are shown in Figure 2 and 3.

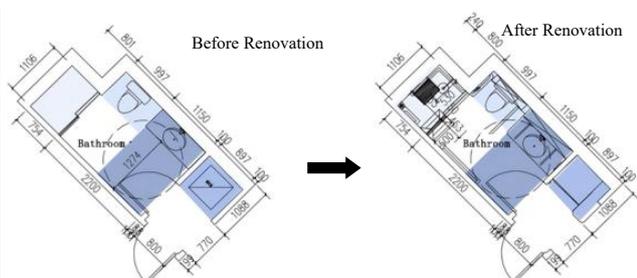


Figure 2: Floor Plan of the Bathroom Adjacent to the Kitchen

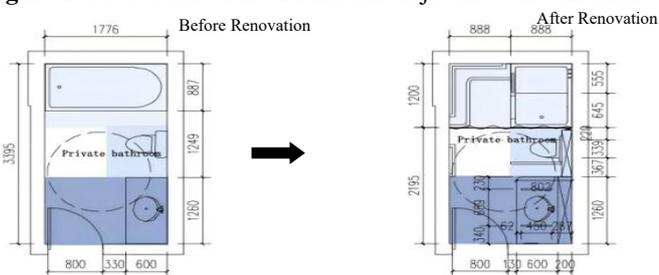


Figure 3: Floor Plan of the Master Bedroom En-Suite Bathroom

4.1.1 Toilet Area

Since both bathrooms share identical issues in the toilet area, a unified renovation scheme is adopted. The main problems in the original toilet area included insufficient lateral clearance, lack of storage function, absence of grab bars, and no emergency alarm device, resulting in poor overall safety and convenience. Therefore, this design is optimized under the premise of conforming to ergonomics and age-friendly standards.

For spatial adjustment, local inward retraction of the left and right sides is implemented to widen the lateral clearance of the toilet area. This facilitates the installation of lateral grab bars and provides space for future assisted operation by caregivers. The toilet selected features a water tank with a large lever-style flush handle and is equipped with a smart toilet seat. This smart toilet seat includes features such as warm

water cleansing, automatic drying, heated seating, and anti-bacterial deodorization to enhance comfort and hygiene.

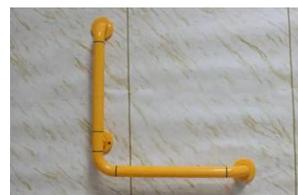


Figure 4: L-Shaped Grab Bar in the Toilet Area (Source: Internet)



Figure 5: Flip-Up Grab Bar in the Toilet Area (Source: Internet)

In terms of detailed design, the toilet paper dispenser is positioned in front of the toilet’s left side for easy access while seated. An L-shaped grab bar (Figure 4) is installed on the side wall, integrated with a shelf and a tissue holder. A flip-up grab bar (Figure 5) is added on the open side, which can be folded away when not in use for easy cleaning and caregiving access. For safety facilities, an emergency alarm button is placed next to the toilet at the same height as a conventional switch.

A low-level “breathing light” is installed underneath to guide movement at night. A storage cabinet is added above, a towel bar is placed on the opposite wall, and anti-slip mats are placed on the floor to enhance safety and storage convenience. Through these design improvements, the toilet area achieves comprehensive optimization in space utilization, safety protection, and comfort experience, significantly elevating the overall age-friendliness and future sustainable usability. Specific design details are shown in Figures 6–9, with related dimensions in Table 5.

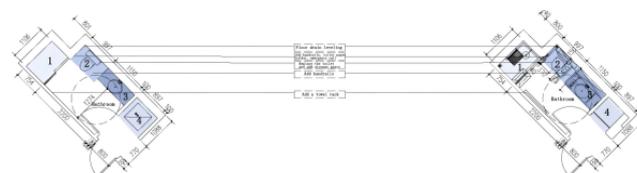


Figure 6: Modified Floor Plan of the Toilet Area in the Kitchen-Side Bathroom (Source: Self-drawn)

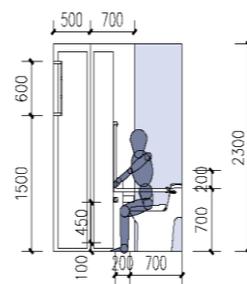


Figure 7: Modified Elevation of the Toilet Area in the Kitchen-Side Bathroom (Source: Self-drawn)

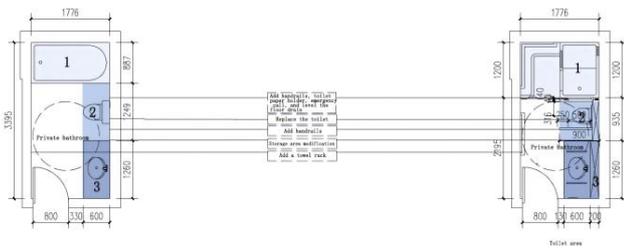


Figure 8: Modified Floor Plan of the Toilet Area in the Master En-Suite Bathroom (Source: Self-drawn)

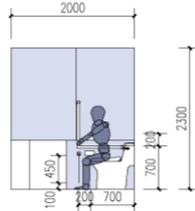


Figure 9: Modified Elevation of the Toilet Area in the Master En-Suite Bathroom (Source: Self-drawn)

Table 5: Dimensions of the Modified Toilet Area (Source: Self-drawn)

Renovation Item		Dimensional Specificatio	
Bathroom Adjacent to Kitchen and Master En-Suite Bathroom	Toilet Replacement	Toilet center-line distance to side wall: 600 mm	
	Addition of Grab Bars	“L”-Shaped Grab Bar	Horizontal bar height: 700 mm; Vertical bar distance from toilet front edge: 200 mm; Vertical bar top height from floor: 1400 mm
		Flip-Up Horizontal Grab Bar	Horizontal bar height: 700 mm; Distance from toilet center-line: 370 mm
	Toilet Paper Dispenser	Distance from toilet front edge: 200 mm; Height: 550 mm	
	Towel Bar	Height on the wall opposite the toilet: 1800 mm	
	Storage Cabinet	Located on the wall corresponding to the toilet, at a height of 1800 mm	
	Pull-Cord Emergency Call System	Right side of the toilet, height: 1100 mm	
	Low-Level Breathing Light (Nightlight)	Below the toilet, height: 50 mm	

4.1.2 Shower Area

The shower area is the section with the highest potential risk in the daily life of the elderly, making it the focus of this renovation. Given the structural and usage differences between the two bathrooms, the renovation schemes for the kitchen-side bathroom and the master bedroom bathroom are described separately.

1) Design of the Shower Area in the Kitchen-Side Bathroom

This bathroom uses a fixed shower head, and the original problems included a lack of resting facilities, insufficient grab bars, a non-adjustable shower head, and a 20mm threshold separating the wet and dry areas. To address this, the design relocates the shower head and installs a sliding base to accommodate different heights and postures. The renovated shower area has dimensions of 1050mm,1460 mm long. The threshold is removed and replaced with a 750 mm long, gently sloped anti-slip transition. A long-strip floor drain is set at the boundary of the slope to ensure smooth drainage and safe passage.



Figure 10: L-Shaped Grab Bar in the Shower Area (Source: Self-drawn)

A foldable seat, 420mm high and 400 mm wide, is installed within the shower area. This allows for seated showering or mid-shower rest. An L-shaped grab bar (Figure 10) is added along the wall to assist with standing and movement. The emergency alarm button is a pull-cord device positioned away from direct water spray to prevent accidental activation.

The faucet is a thermostatic control type, maintaining the water temperature at 45±3°, with clear markings differentiating the cold and hot directions. The faucet height is 1000mm from the floor. A warm-light shower heater is installed overhead to maintain a suitable temperature. Anti-slip mats are placed both inside and outside the shower area. Specific design details are shown in Figures 11 and 12, with related dimensions in Table 6.

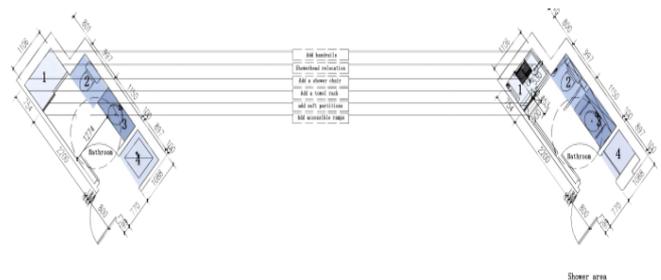


Figure 11: Modified Floor Plan of the Shower Area in the Kitchen-Side Bathroom (Source: Self-drawn)

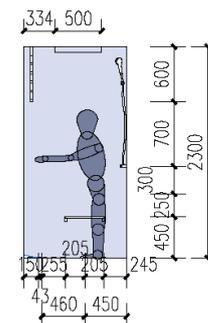


Figure 12: Modified Elevation of the Shower Area in the Kitchen-Side Bathroom (Source: Self-drawn)

Table 6: Dimensions of the Modified Shower Area (Source: Self-drawn)

Renovation Item		Dimensional Specification	
Bathroom Adjacent to Kitchen	Shower head Adjustment	Shower head center-line distance to side wall: 450 mm; Sliding base lowest point: 1235 mm; Highest point: 1900 mm; Shower valve height: 1000 mm	
	Addition of Grab Bars	“L”-Shaped Grab Bar	Horizontal bar height: 700 mm; Vertical bar top height from floor: 1400 mm
		Foldable Horizontal Grab Bar	Horizontal bar height: 700 mm
Addition of a Foldable Shower Seat		Shower seat center-line distance to side wall: 450 mm; Height: 450 mm	

Pull-Cord Emergency Call System	Left side wall of the shower seat, height: 1100 mm
Exterior Gentle Slope at Threshold	Height from floor: 20 mm; Width: 770 mm
Multi-functional Bathroom Heater (Yuba)	Yuba center-line distance to side wall: 584 mm

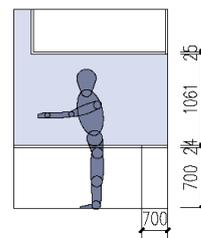


Figure 15: Modified Elevation of the Shower Area in the Master En-Suite Bathroom (Source: Self-drawn)

2) Design of the Shower Area in the Master Bedroom Bathroom



Figure 13: Age-Friendly Seated Bathtub in the Shower Area (Source: Self-drawn)

The master bedroom bathroom originally featured a traditional bathtub, presenting issues such as excessive depth and height, and a lack of grab bars and an emergency alarm. The renovation replaces the bathtub, rotating it from an east-west to a north-south orientation, and installs an age-friendly seated bathtub (Figure 13). This seated bathtub has dimensions of 890mm wide, an internal length of 1200mm, an external edge height of 450mm, and an entrance width of 600mm. The faucet is located 300mm from the edge, facilitating wheelchair access. Anti-slip Mats are placed both inside and outside the tub to ensure safety.

To enhance the convenience of standing up, a 550mm wide platform is set outside the tub. An L-shaped grab bar is installed on the side wall, and a small grab bar is added inside the tub to support seated operation. The alarm device is also a pull-cord design, installed on the side wall where it will not be sprayed by water, allowing access from both sitting and semi-standing postures. With the tub’s change in direction, an open storage cabinet and towel rack are added to the west side (counter height 700mm depth 150mm, reducing the need to bend over. A warm-light shower heater is installed overhead, with the control panel located outside the wet zone. A soft, openable partition is used to allow for future entry of caregiving equipment. The faucet is thermostatic control, with the water temperature maintained at $45^{\circ}\pm 3^{\circ}$. Specific design details are shown in Figures 14 and 15, with related dimensions in Table 7.

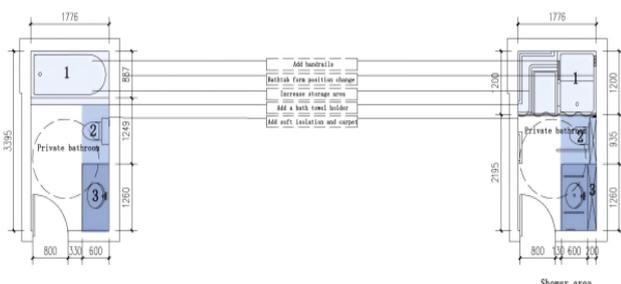


Figure 14: Modified Floor Plan of the Shower Area in the Master En-Suite Bathroom (Source: Self-drawn)

Table 7: Dimensions of the Modified Shower Area (Source: Self-drawn)

	Renovation Item	Dimensional Specification	
Master En-Suite Bathroom	Bathtub Adjustment	Shower head center-line distance to side wall: 600 mm; Bathtub valve height: 750 mm	
	Addition of Grab Bars	“L”-Shaped Grab Bar	Horizontal bar height: 700 mm; Vertical bar top height from floor: 1400 mm
		Horizontal Grab Bar	Horizontal bar height: 700 mm
	Pull-Cord Emergency Call System	Right side wall of the bathtub, height: 1100 mm	
	Multi-functional Bathroom Heater(Yuba)	Yuba center-line distance to side wall: 888 mm	
	Storage Cabinet	Storage cabinet height: 700 mm	
	Towel Rack	Height on the wall opposite the bathtub: 1800 mm	

4.1.3 Sink Area

The sink areas in both bathrooms face similar challenges, primarily low space utilization and inappropriate human-machine dimensions. In the existing setup, the space beneath the sink is insufficient, causing fatigue in the waist and legs for the elderly during prolonged standing. The faucet is too close to the side wall, restricting arm movement. Disorganized storage leads to space wastage, and inadequate lighting compromises safety and comfort during washing.

To address these issues, the design centers on “functional integration and accessibility optimization,” proposing an integrated strategy for washing, storage, and toileting functions. In terms of human-machine dimensions, the size of the sink and washing area is appropriately adjusted: the sink’s center line is 450mm from the side wall, the depth is 600mm, and the height is approximately 800mm. These dimensions accommodate both standing and seated washing needs of the elderly. A clearance space of 600mm high and 250mm deep is reserved beneath the sink to allow for wheelchair access or seated use. An L-shaped grab bar is added to the side wall to provide support and assistance when standing up. Hidden grab bars are integrated within the vanity unit, maintaining visual neatness while enhancing safety and stability during seated washing.

Regarding safety and auxiliary facilities, a light switch, alarm, and power outlet are placed on the right side wall, with the outlet covered by a waterproof protective shield to prevent moisture infiltration. The lighting system uses multi-color temperature, adjustable-intensity overhead lights. A return light strip is embedded beneath the mirror cabinet to enhance countertop illumination. A “breathing light” is added beneath the sink to provide gentle directional light at night, preventing falls or collisions.

For storage and mirror design, two storage areas are created: one connected to the vanity unit for temporary items, and the other as a mirror cabinet storage unit. The latter combines an anti-fog mirror surface with multi-layer storage. The bottom edge of the mirror cabinet is 250mm above the countertop, with a hidden light source at the bottom to enhance illumination. A retractable magnifying mirror is added to the side to facilitate shaving or grooming for the elderly. Through these renovations, the sink area is significantly improved in safety, comfort, and usage efficiency, achieving coordination among space utilization, functional integration, and human-machine dimensions. Specific renovation details are shown in Figures 16–19, with detailed dimensions in Table 8.

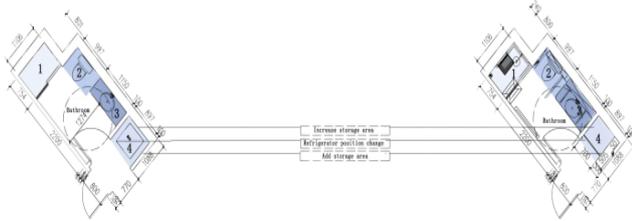


Figure 16: Modified Floor Plan of the Vanity Area in the Kitchen-Side Bathroom (Source: Self-drawn)

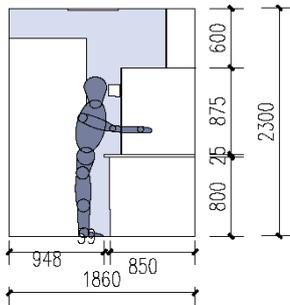


Figure 17: Modified Elevation of the Vanity Area in the Kitchen-Side Bathroom (Source: Self-drawn)

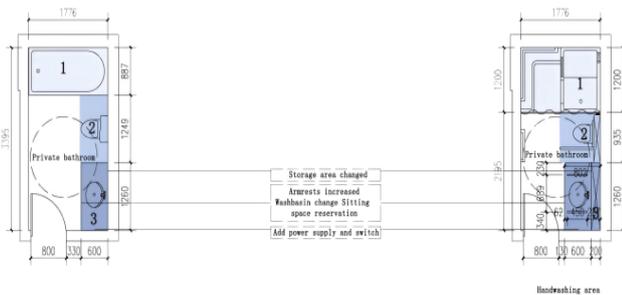


Figure 18: Modified Floor Plan of the Vanity Area in the Master En-Suite Bathroom (Source: Self-drawn)

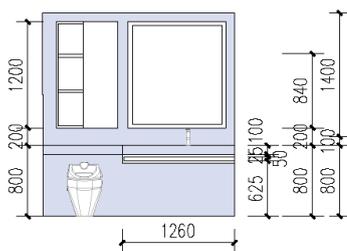


Figure 19: Modified Elevation of the Vanity Area in the Master En-Suite Bathroom (Source: Self-drawn)

Table 8: Dimensions of the Modified Vanity Area (Source: Self-drawn)

Self-drawn)

Renovation Item	Dimensional Specification	
	Sink Adjustment	Faucet center-line distance to side wall:
Faucet center-line distance to side wall:		450 mm
Addition of a recessed groove beneath the sink for seated support		
Reserved height clearance beneath the sink:		650 mm
Mirror bottom edge distance from sink:		250 mm
Temporary Storage Area	Height: 800 mm	
Cabinet Storage Area	Bottom edge height from floor: 1000 mm	
Lighting	Light source center-line distance to side wall: 630 mm	
Pull-Cord Emergency Call System	Right side wall of the sink, height: 1400 mm	
Low-Level Breathing Light (Nightlight)	Bottom edge height from floor: 1000 mm	
Switch and Power Outlet	Right side wall of the sink, height: 1300 mm	

4.1.4 Adjacent Transition Space

Given the differing functional purposes, usage needs, and problem characteristics of the adjacent spaces for the two bathrooms in this unit, targeted renovations are required for each.

1) Adjacent Transition Space for the Kitchen-Side Bathroom

This bathroom shares a transition area with the kitchen, which was originally only used for the washing machine, resulting in single functionality and low utilization. Furthermore, the washing-drying process was cumbersome, causing inconvenience for the elderly in moving laundry and resulting in cross-traffic flow. To address this, the washing machine is relocated to the balcony, which is suitable for drying, creating an integrated washing-drying process. The original location is converted into a functional extension area for the kitchen, used for placing the refrigerator, thus optimizing the kitchen circulation and spatial continuity.

In terms of detailed design, the side wall is partially opened, and a new countertop, 800mm high, is installed, conforming to the standing operation height for the elderly. A movable cart is placed underneath for fetching and placing items. Overhead lighting and a top cabinet are installed to enhance the lighting environment and storage capacity. To prevent moisture diffusion into the kitchen area, an anti-slip mat is laid on the floor to enhance safety. Through circulation reorganization and functional integration, the kitchen and bathroom spaces achieve efficient connection and coordinated use. Specific renovation details are shown in Figures 20 and 21, with detailed dimensions in Table 9.

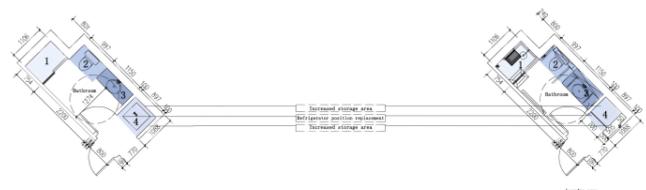


Figure 20: Modified Floor Plan of the Adjacent Transition Space (Kitchen-Side Bathroom) (Source: Self-drawn)

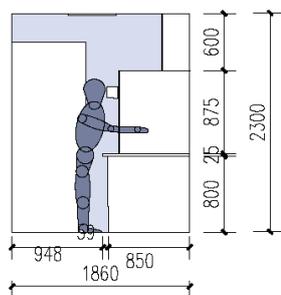


Figure 21: Modified Elevation of the Adjacent Transition Space (Kitchen-Side Bathroom) (Source: Self-drawn)

Table 9: Dimensions of the Modified Adjacent Transition Space (Source: Self-drawn)

Renovation Item	Dimensional Specification
Refrigerator Adjustment	Refrigerator center-line distance to left side wall: 350 mm
Temporary Storage Cart	Height: 800 mm
Cabinet Storage Area	Cabinet bottom edge height from floor: 1700 mm
Lighting	Light source center-line distance to side wall: 930 mm

2) Adjacent Transition Space for the Master Bedroom Bathroom

The area adjacent to the master bedroom bathroom was originally an unused space. The main bedroom door and the bathroom door interfered with each other when opened, affecting passage and safety. The design focuses on “spatial integration and intelligent accessibility optimization”. The original swing door is replaced with an intelligent sliding door that uses a sensor system for automatic, contactless opening and closing. The door body is equipped with a recessed mechanical handle, allowing for manual operation in case of power failure.

For visual and functional enhancements, a cabinet unit and a countertop, 750mm high, are installed on the outside of the sliding door. This serves as both an item placement area and a platform for seated operation. The space beneath the countertop has sufficient depth to accommodate wheelchair activity. The lighting uses multi-color temperature, adjustable-intensity light sources to adapt to different usage scenarios, enhancing spatial comfort and safety. Specific renovation details are shown in Figures 22 and 23, with detailed dimensions in Table 10.

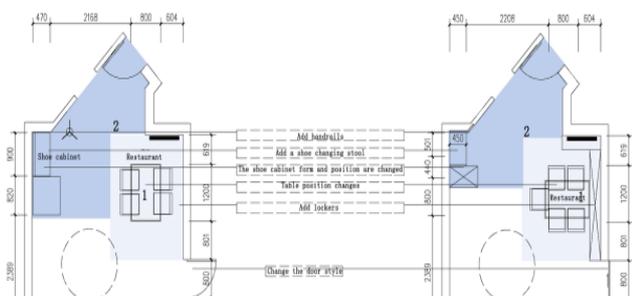


Figure 22: Modified Floor Plan of the Adjacent Transition Space (Master En-Suite Bathroom) (Source: Self-drawn)

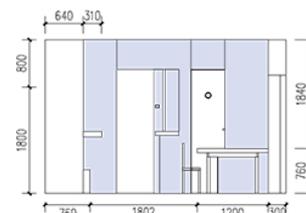


Figure 23: Modified Elevation of the Adjacent Transition Space (Master En-Suite Bathroom) (Source: Self-drawn)

Table 10: Dimensions of the Modified Adjacent Transition Space (Source: Self-drawn)

Renovation Item	Dimensional Specification
Master Bedroom Door	Sliding door width: 1000 mm
Cabinet Storage Area	Cabinet distance from floor (top edge): 2300 mm
Lighting	Light source center-line distance to right side wall: 900 mm
Dining Table Modification	Tabletop height from floor: 750 mm

4.2 Application of VR Technology

This research introduces VR technology to construct a user-centric human-computer interaction verification system, primarily realizing two core functions: virtual roaming and interactive experience. The aim is to transform design verification from a traditional “design presentation” into an “immersive user experience”.

Virtual roaming involves building a high-fidelity virtual 3D environment (Figures 24, 25), allowing users to experience the overall layout, circulation organization, and facility usage effects of the bathroom from a first-person perspective. This function assists the elderly user in familiarizing themselves with the spatial dimensions and usage convenience of the future environment during the design phase, providing intuitive reference for subsequent accessibility optimization.



Figure 24: Post-Renovation VR View of the Master En-Suite Bathroom (Source: Self-drawn)



Figure 25: Post-Renovation VR View of the Kitchen-Side Bathroom (Source: Self-drawn)

The real-time interactive function utilizes a real-time operation and behavioral feedback mechanism (Figure 26), enabling designers to dynamically observe users’ operational habits and behavioral trajectories in the virtual space. This allows for accurate capture of individual differences and genuine needs. Consequently, designers can make targeted

adjustments to spatial dimensions, facility placement, and detail processing.



Figure 26: VR Rendering of the Bathroom (Source: Self-drawn)

The application of VR technology effectively enhances the participation and scientific rigor of the design process, ensuring that the design outcome aligns more closely with the actual physiological and psychological characteristics of the elderly. It provides visual and operable technical support for subsequent design optimization and accessibility evaluation.

4.2.1 Roaming Design

This research constructs an immersive spatial experience environment based on VR technology (Figure 27) to authentically restore the bathroom's spatial layout and facility dimensions, aiding in the verification of the age-friendly design's scientific validity and rationality.



Figure 27: VR Walk through Simulation of the Bathroom (Source: Self-drawn)

System parameters are strictly set according to ergonomic standards. The VR perspective is precisely adjusted based on the actual height of the two residents: the female resident's perspective height is set to 1.60m, and the male resident's perspective height is set to 1.75m. Considering the height differences and daily behavioral characteristics of the two residents, two modes of movement—"radar positioning mode" and "natural walking mode"—are provided to dynamically adapt to the interactive demands of different experience scenarios. Furthermore, the VR system supports the dynamic simulation of three body postures: standing, sitting, and squatting. This enables users to verify the space's adaptability and reachability from multiple angles.

For instance, through first-person perspective and interaction with a virtual hand model, users can intuitively check whether the height of the vanity unit, the depth of the faucet, and the installation height of the side wall grab bars comply with ergonomic and safety standards. During the seated experience, users can specifically verify whether the reserved space beneath the sink meets the requirements for leg movement and wheelchair insertion. The simulation experience achieves high-precision interactive feedback, allowing users to assess whether the height and distance relationship between the toilet and the side grab bars, and the height settings for the shower seat and sliding shower head, comply with the usage habits of

the elderly. This facilitates a comprehensive, dynamic evaluation of facility placement and operational convenience.

Considering the potential functional decline of advanced-age users, the design incorporates considerations for latent needs (such as difficulty standing up or squatting) into the spatial layout and system simulation. The system pre-sets a wheelchair perspective height of 1.00m and a minimum required passage width of 900mm. When the spatial layout cannot meet the requirements for wheelchair movement or turning, the system provides warnings and physical blocking via a "virtual wall". This helps both the designer and the user collaboratively identify and optimize spatial barriers, ensuring the design's sustainable adaptability.

4.2.2 Interactive Design

This design introduces a VR interaction function module into the research on residential space accessibility. Its core features include two major dimensions: "Component and Material Switching" and "Component Drag and Adjustment". This design aims to establish a real-time information feedback loop among the user, the designer, and the virtual space, thereby achieving dynamic optimization of the design scheme and enhancing the scientific validity of design decisions and user participation.

By pre-setting multiple design schemes and corresponding interactive buttons (Figure 28), the system enables users to intuitively experience the differentiated impact of various component and material combinations on spatial atmosphere, visual perception, and usage convenience within the immersive environment. Users can achieve scene switching via touch operation or laser pointing interaction methods. This allows for immediate comparison of the perceived evaluation results for different configurations, such as grab bar types, shower seat styles, and wall materials, effectively promoting the rapid screening and determination of the design scheme.

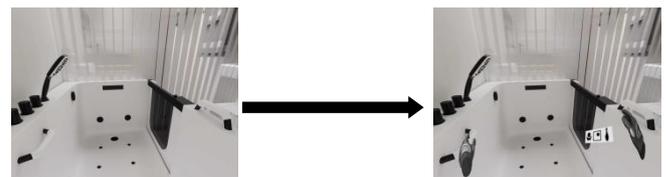


Figure 28: VR Scene and Material Interaction Simulation of the Bathroom (Source: Self-drawn)

This function allows users to directly participate in the arrangement and adjustment of design components within the virtual space (Figure 29). The system is connected to a database and provides a model inventory, enabling users to independently select, drag, and reposition required components during the experience. For instance, if the initial placement of an accessible grab bar does not align with the elderly user's gripping needs, or if the shower seat height is inconsistent with user habits, the user can directly perform a drag-and-drop adjustment. This function significantly enhances the efficiency of design communication and feedback, provides elderly users with a stronger sense of ownership and participation in the design experience, and effectively prevents time and resource wastage caused by discrepancies in requirements during the project implementation phase.



Figure 29: VR Object Drag-and-Drop Interaction Simulation of the Bathroom (Source: Self-drawn)

The VR interactive design establishes a dynamic, visualized platform for accessible design verification, achieving a multi-dimensional information loop among the user, the space, and the designer. This platform allows elderly users to directly participate in the design process as the central subjects. Designers can further optimize the spatial layout and component configuration based on interactive feedback, ultimately enhancing the precision and sustainability of age-friendly residential space design.

5. Conclusion

This paper focuses on the construction of accessible environments in residential spaces, centering on the application of Virtual Reality (VR) technology in age-friendly design. By introducing VR into the traditional interior design process, an integrated verification platform—encompassing immersive experience, dynamic roaming, and human-computer interaction—is constructed. This provides an intuitive and scientific means of expression and evaluation for accessible design.

Compared to traditional two-dimensional drawings and static renderings, VR technology creates a more efficient communication bridge between designers and users through its immersiveness and interactivity. Designers can use it to achieve precise identification and real-time adjustment of needs, enhancing the scientific validity of design decisions. Users, in turn, can experience the spatial effect from a first-person perspective in advance, verifying the rationality of dimensions and facility placement. This reduces the discrepancy between “design and usage” and strengthens spatial adaptability and humanistic care.

Nonetheless, the current application of VR technology in accessible design is still constrained by technical bottlenecks such as motion sickness, insufficient tactile feedback, and limited simulation fidelity. Further enhancement is needed in areas such as software and hardware integration and optimization of interaction logic. In the future, VR technology can be deeply integrated with AI, Building Information Modeling (BIM), and the Internet of Things (IoT). This integration can promote its multi-dimensional application in urban renewal, community renovation, and public service facility planning, offering technical support and innovative pathways for constructing inclusive, intelligent, and sustainable living environments.

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