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Developing age-friendly spaces through a gerontechnological lens: a systemic framework based on FDM-DANP analysis

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With the acceleration of population aging and the spread of smart technologies, integrating Gerontechnology with spatial design has become an urgent challenge. Although previous studies have examined technology acceptance and environmental adaptation, they have lacked a systematic framework to capture multiple dimensions and their interdependencies with empirical evidence. This study proposes a two-stage integrated framework that combines the Fuzzy Delphi Method (FDM) and the Decision-Making Trial and Evaluation Laboratory-based Analytic Network Process (DANP) to identify and quantify the key factors and causal structures of integrating Gerontechnology into spatial design. This study utilized FDM to screen out 15 key indicators. The DANP results show that within “Age-Friendly Design,” C₁₀: Fault-tolerant spatial configuration received the highest weight (global weight 26.42%), followed by C₉: Comfortable ambient temperature under “Living Space” (7.18%). These findings highlight the central role of fault-tolerant spatial configuration and environmental comfort in the integrated framework. In DANP, the consensus index of experts for all dimensions exceeded 95%, confirming the robustness of the findings. In addition, the DEMATEL results reveal that Gerontechnology Application has a primary driving effect on other dimensions and elements in the causal network, showing its key role in system integration. These findings provide policymakers and practitioners with clear references for prioritization and spatial planning, and also offer actionable decision support for smart spatial strategies and cross-sector collaboration in the context of healthy aging.

KEYWORDS

age-friendly, Gerontechnology, multi-criteria decision-making (MCDM), systematic integration, spatial design

1 Introduction

Technological and medical innovations have emerged as key contributors to life extension, enhancing overall social welfare and facilitating the transition toward healthy aging. This trend has introduced new challenges in the allocation of healthcare and caregiving resources, while simultaneously generating institutional and technological demands in fundamental domains such as housing, mobility, and social participation. Previous studies have suggested that smart cities represent a promising approach for addressing the societal implications of population aging (1). Gerontechnology, in particular, is widely recognized as a foundational component in enabling healthy aging within the framework of smart cities (2, 3).

Gerontechnology refers to the interdisciplinary integration of gerontology and technological sciences, aimed at promoting the health, independence, and overall life satisfaction of older adults (4–8). Numerous studies have demonstrated that the effective integration of Gerontechnology into the daily lives of older adults can improve their functional independence, mitigate physical decline, and enhance social engagement (9, 10). However, despite the widely acknowledged potential of technology and the ongoing development of Gerontechnology devices and services, older adults continue to experience significant barriers to technology adoption compared to younger or more digitally literate populations (11, 12). Meanwhile, older adults continue to report low levels of technology acceptance and user satisfaction in everyday living contexts (13–15). Peek et al. (16) emphasized that the compatibility and adaptability between technology and the physical environment critically shape older adults' willingness to adopt Gerontechnology. For instance, a mismatch between road safety conditions and safety technologies may reduce their acceptance of transportation-related Gerontechnology. Moreover, an increasing body of research has highlighted older adults' reservations and skepticism regarding the misalignment between technology and environmental contexts (119, 120). This suggests that in the design of age-friendly environments, there remain challenges related to the lack of synchronization between Gerontechnology systems and spatial infrastructures, leading to a disconnection between Gerontechnology Applications and everyday living contexts (17, 18). Therefore, in response to the growing demand for age-friendly environments, identifying the key factors that influence the integration of Gerontechnology into physical spaces is of critical importance.

In recent years, Multi-Criteria Decision-Making (MCDM) methods have been extensively applied in studies on age-friendly environments and facility design. For instance, Jiravanichkul et al. (19) employed the Analytic Hierarchy Process (AHP) to develop evaluation criteria for Thailand's Well-Being Environment and Age-Friendly Communities, emphasizing that local governments should account for the unique environmental needs of older adults in planning. Zarghami et al. (20) applied AHP to assess factors influencing quality of life in Iranian older adults housing, revealing that physical and perceptual aspects of design carried the greatest weight in decision-making. Similarly, Weck et al. (21) utilized Multiple Criteria Decision Aid (MCDA) to examine how to balance sustainability and age-friendly requirements in smart living environments. Collectively, these studies demonstrate that MCDM can provide a structured indicator system and a basis for decision support in age-friendly design. Nevertheless, existing research remains largely focused on single dimensions and lacks an analytical framework to systematically integrate Gerontechnology with the design of age-friendly spaces. At the same time, these studies have tended to overlook spatial environments as active components in the design process, without adequately addressing the need for coordinated spatial planning and structural compatibility. Sometimes, home modifications even led to unintended negative consequences for older adults, and in some cases, even exacerbated their living challenges (17, 18, 22–24). Therefore, establishing effective integration between spatial systems and Gerontechnology has become a pressing challenge for both academic researchers and industry practitioners.

Under the influence of the silver economy, both Gerontechnology-related industries and urban governance frameworks have begun to reassess the evolving lifestyles of older adults (25, 26). However, the

current development of Gerontechnology remains largely product-driven, with design efforts heavily focused on ergonomics while overlooking the contextual realities of older adults' living environments (2, 18). Simultaneously, prior research has tended to treat technology and Living Space as distinct domains, lacking comprehensive frameworks to examine their interrelations and overlooking the structural interdependence between spatial configurations and technological functionalities (14). In addition, prior studies have identified the lack of user-centered design as a primary barrier to the adoption of smart home systems, resulting in misalignment between users' needs, capabilities, and the functionalities of available technologies (27, 28). Therefore, as technological systems grow increasingly complex, there is an urgent need to advance age-friendly research and ensure that its outcomes are effectively translated into the development of Gerontechnology (29).

Notably, the integration of Gerontechnology with spatial environments often entails substantial implementation and maintenance costs (30). Given the complexity of influencing factors, such financial burdens risk exacerbating the digital divide, potentially excluding segments of the older population from equitable access to smart living environments (29, 31). This underscores the need for age-friendly integration frameworks to incorporate considerations of resource allocation, offering decision-makers cost-effective models that translate into practical and affordable strategies for older adults. Therefore, the primary objective of this study is to investigate how Gerontechnology can be effectively integrated into specific living and spatial contexts to address the practical needs of older adults across key domains of age-friendly environments, including housing, health, and safety.

Accordingly, this study addresses the following research questions:

- 1) How can the key factors underlying the integration of Gerontechnology and spatial design be identified from an age-friendly perspective?
- 2) How can the causal relationships and relative influence among these factors be systematically modeled to develop a cost-effective and strategically meaningful integration framework?

To answer these questions, this study aims to identify the key factors involved in the integration of Gerontechnology and spatial environments, and to elucidate their causal structure and relative influence.

The methodology adopted in this study consists of the following steps: First, to identify key factors, the Fuzzy Delphi Method (FDM) is applied to refine potential indicators derived from the literature, resulting in an expert-validated framework. FDM is particularly effective in addressing high-cost issues by minimizing the allocation of resources to unnecessary or non-demand-driven components. This step lays the groundwork for developing integration strategies that are both feasible and affordable. Subsequently, the DEMATEL-based Analytic Network Process (DANP) is employed to analyze the interdependencies among the selected indicators. DEMATEL is well-suited to uncovering complex causal interactions among criteria, while ANP enables the prioritization of these factors, assisting decision-makers in resource allocation and strategic planning (32, 33). DEMATEL is well-suited to uncovering complex causal interactions among criteria, while ANP enables the prioritization of these factors, assisting decision-makers in resource allocation and strategic planning

(32, 33). By grounding this framework in the convergence of everyday environments and technology, the study contributes to advancing the sustainable development and practical realization of smart cities in aging societies.

2 Literature reviews

2.1 Research on Gerontechnology

Pilotto et al. (8) and Parra-Rodríguez et al. (7) defined and classified Gerontechnology into three main domains: (i) Information and communication technologies (ICT), referring to tools that facilitate access to information and communication, such as digital platforms, telemedicine programs, and the application of artificial intelligence in healthcare; (ii) Assistive technologies aimed at preserving the independence and safety of older adults, including environmental monitoring systems, personal sensors, and smart home devices; and (iii) Human-machine interaction technologies that support the therapy and rehabilitation of older individuals with mobility or cognitive impairments, such as robotics, exergames, and virtual reality-based interventions, with demonstrated clinical benefits and potential to enhance social engagement. Prior research on Gerontechnology has predominantly relied on classical technology acceptance frameworks, particularly the Technology Acceptance Model (TAM) [e.g., (13, 34, 35)] and the Unified Theory of Acceptance and Use of Technology (UTAUT) [e.g., (15, 36–38)], to investigate various Gerontechnology use scenarios. In examining older adults' engagement with technology, existing studies have primarily focused on individual-level psychological determinants (39, 40), including perceived usefulness (41), technology-related anxiety (42, 43), perceived ease of use (2), and behavioral intention (39).

The aforementioned studies have provided valuable insights into older adults' intention to adopt Gerontechnology, offering useful implications for its future development and implementation. However, the adoption of technology among older adults is shaped not only by psychological determinants but also by contextual factors such as health conditions and specific technological needs (44). Melander-Wikman et al. (45) observed that older adults may be willing to compromise on privacy in exchange for enhanced mobility and safety, provided they retain autonomy over how such technologies such as alarm systems are used. This suggests that older adults' acceptance behaviors may vary according to the function and nature of the technology. Therefore, the application of Gerontechnology should be guided by principles of selectivity and integration, thereby ensuring long term sustainability while maintaining cost effectiveness.

2.2 Spatial dimensions of aging

2.2.1 Spatial environment

Space, as a socially constructed entity shaped by multiple environmental factors, plays an enduring role in shaping social relations, power dynamics, and structural inequalities (17, 46). As individuals age and their physiological and psychological needs evolve, spatial environments may give rise to new forms of age-related spatial inequality (47). For instance, the digital divide

associated with the advancement of Gerontechnology may marginalize certain communities and populations by limiting their equitable access to smart environments (29). Against this backdrop, a growing body of research has highlighted the critical role of spatial environments in fostering inclusive and sustainable urban development, which in turn has significant implications for promoting healthy aging among older populations (17). On one hand, there is increasing awareness of the health-promoting benefits of Public Spaces for older adults, particularly the importance of high-quality public environments in mitigating loneliness and reducing the risk of social exclusion (48, 49). On the other hand, residential environments play a fundamental role in supporting the daily well-being and quality of life of aging individuals (50). Compared to other age groups, older adults tend to spend a greater proportion of their time within the home, making factors such as comfort, safety, and design quality in residential spaces directly influential on their overall well-being (50, 51).

Drawing on insights from health geography and environmental gerontology, earlier scholars began incorporating physical environments into aging research (16). For example, Melander-Wikman et al. (45) indicated that older adults' adoption decisions may be shaped by mobility and safety related infrastructure, while Huang and Oteng (44) highlighted that community infrastructure and spatial support may play a critical role in enhancing Gerontechnology adoption. Nevertheless, prior studies have primarily focused on the influence of single environmental dimensions, without adequately addressing the potential synergies between Gerontechnology, the spatial contexts in which older adults live, and their associated spatial perceptions. Therefore, this study considers real life spatial contexts as a key dimension and, drawing on the concept of Gerontechnology, proposes a framework for space and technology integration grounded in real world contexts. This framework offers valuable insights into how Gerontechnology can be leveraged to promote active aging.

2.2.2 Age-friendly design

Human-centric has been widely recognized as a foundational principle for enhancing the well-being, autonomy, and health-related rights of older adults (52). As aging societies evolve, human-centric approaches have been embedded in both geriatric care and technological development. Notable paradigms include relationship-centered care (53–56), person-centered care (54, 57, 58), and user-centric design (27, 59–61). User-centric design, in particular, emphasizes that the development of Gerontechnology must accommodate the diverse needs, abilities, and psychological responses of end users (27, 59). Failure to do so may result in technology rejection by older adults, often due to misalignments between the product's functionalities and users' perceptions, attitudes, or lifestyle preferences (62).

2.2.3 Gerontechnology application

The development of intelligent spatial environments has been shown to support older adults in coping more effectively with the functional and lifestyle challenges associated with aging (63). Gerontechnology are designed to leverage emerging technologies and devices to enhance the autonomy, safety, health monitoring, and overall well-being of older adults (63). Prior studies have emphasized that the design of Gerontechnology Applications should prioritize integrated environmental monitoring systems, user-environment

interactivity, and intelligent, user-friendly assistive functionalities (64, 65).

The scope of Gerontechnology addressed in this study encompasses multiple design and technological dimensions aimed at enhancing the quality of life and care for older adults, including emergency alert systems (66), fall detection mechanisms, and electronic medical record functions (65). However, there remains a lack of targeted frameworks for integrating age-friendly Gerontechnology with diverse spatial environments. Taken together, prior studies indicate that spatial environments, intelligent technologies, and human-centered, age-friendly design significantly affect older adults' mental well-being and exposure to structural inequality. Therefore, building on prior literature, this study identifies four dimensions and corresponding evaluation indicators (see Table 1). These dimensions focus on spatial integration from an older adult centered perspective, encompassing Public Spaces, Living Spaces, Age-Friendly Design, and Gerontechnology Application. These dimensions focus on spatial integration from an older adult-centered perspective, encompassing Public Space, Living Space, Gerontechnology Applications, and Age-Friendly Design. The objective is to develop an operational framework that can directly support decision-making and design planning, while systematically offering guidance for the sustainable development and practice of smart cities in aging societies.

3 Methodology and data collection

3.1 Research methods and procedures

To address the aforementioned issues, this study employs an expert-based multiple-criteria decision-making (MCDM) approach to develop a systematic age-friendly spatial evaluation framework. Specifically, the FDM is first used to identify the critical factors. Subsequently, the DEMATEL technique is applied to analyze the causal relationships and interactions among these factors. Finally, the DANP is integrated to further derive the relative weights of each factor, as illustrated in Figure 1.

3.1.1 Fuzzy Delphi method

Given the complexity and multidimensionality of smart aging spaces, the FDM is employed to validate expert consensus and to refine the key components of the age-friendly spatial framework. FDM is a MCDM technique designed to manage uncertainty and imprecise information in expert evaluations. Its underlying rationale lies in the integration of fuzzy logic and the Delphi method, enabling structured expert judgment through the use of linguistic variables and fuzzy number processing for problem assessment and decision-making. In early studies, Jeng (67) frequently combined fuzzy theory with the Delphi technique to identify relevant variables and potential evaluation indicators within assessment frameworks. The FDM has since been widely applied in planning and evaluation research across domains such as regional governance, community management, and spatial design (68–71). Compared with the traditional Delphi approach, the fuzzy-enhanced method offers several advantages, including:

- 1) Fewer iterative survey rounds.
- 2) Enhanced accuracy in capturing expert knowledge.

- 3) Effective engagement of domain-relevant experts.
- 4) Time and cost efficiency in the evaluation process.

The computational procedures are as follows:

Step 1: For each indicator, calculate the minimum values among all experts' lower bound (l) and upper bound (u) estimates, and the geometric mean (m) of the fuzzy numbers representing expert judgments.

Step 2: Calculate the crisp value o_i using Equation 1.

$$o = o_i = \frac{l_i + m_i + u_i}{3}, i = 1, 2, \dots, n \quad (1)$$

Step 3: The potential factors are denoted as $I_1 \dots I_n$, and the Interquartile Range (IQR) is employed to define a consensus threshold. Indicators meeting this criterion are retained as key factors, labeled ($C_1 \dots C_n$).

3.1.2 DEMATEL

In practical decision-making contexts, the factors involved often exhibit highly complex and intertwined relationships, making it difficult for traditional analytical approaches to uncover the underlying causal mechanisms. To address this challenge, Gabus and Fontela (72) introduced the DEMATEL method (73), which was developed to assist researchers and decision-makers in identifying both direct and indirect influences among factors through a systems-thinking perspective, thereby elucidating the causal structure underlying complex problems.

To uncover the intricate causal relationships and pathways of influence within decision-making systems, this study employs the DEMATEL method to identify the core factors involved in the development of age-friendly environments. This approach supports researchers and decision-makers in pinpointing critical issues, thereby enhancing the appropriateness of intelligent spaces for aging populations. DEMATEL effectively differentiates between driving and affected factors and constructs a clear structure of interdependencies (74–79). The analytical procedure is outlined as follows:

Step 1: Calculate the initial average matrix A .

Experts are invited to perform pairwise comparisons among the factors and assign scores on a scale from 0 to 4, representing levels of influence: “no influence,” “low influence,” “moderate influence,” “high influence,” and “very high influence.” The assessments are then aggregated using Equation 2 to compute the resulting initial average matrix A , where N denotes the total number of k th experts involved in the evaluation.

$$A = \frac{1}{N} \sum_{k=1}^N A_{ij}^k$$

$$= \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{mj} & \cdots & a_{nn} \end{bmatrix} \quad (2)$$

Equation 3 is then applied to assess the degree of consensus among the experts. A confidence level exceeding 95% suggests that the expert evaluations are stable. If the confidence level falls below 95%, Equation 2 must be recalculated, the reliability of the collected data

TABLE 1 Descriptions of potential dimensions and associated criteria.

Criteria		Description	Reference
Dimension 1: Public Space			
I_1	Cleanliness of public spaces	Public areas are clean and pleasant.	(48, 98–100, 102, 103, 106)
I_2	Quantity and safety of green spaces and outdoor seating	Sufficient green spaces and outdoor seating are provided, well-maintained and safe.	
I_3	Sidewalk maintenance and exclusivity	Sidewalks are well-maintained, free of obstructions, and designated for pedestrian use only.	
I_4	Sidewalk material, width, and leveling	Sidewalks are slip-resistant, wide enough for wheelchairs, and curbs are lowered to road level.	
I_5	Number and safety of pedestrian crossings	Crossings are adequate and safe for individuals with various disabilities, including anti-slip markings, visual and audio cues, and sufficient crossing time.	
I_6	Driver yielding behavior	Drivers yield to pedestrians at intersections and designated crossings.	
I_7	Separation of bicycles from pedestrian paths	Bicycle lanes are separated from pedestrian pathways and sidewalks.	
I_8	Outdoor safety enhancement measures	Adequate street lighting, police patrols, and community education enhance outdoor safety.	
I_9	Service concentration	Services are grouped and accessible.	
I_{10}	Special customer service arrangements	Separate lines or service counters are available for older adults.	
I_{11}	Indoor and outdoor signage	Good signage is provided both inside and outside buildings.	
I_{12}	Indoor and outdoor seating	Sufficient seating is available in and around buildings.	
I_{13}	Indoor and outdoor restrooms	Adequate restroom facilities are available both inside and outside buildings.	
I_{14}	Indoor and outdoor accessible features	Facilities include elevators, ramps, handrails, stairways, and non-slip walkways.	
Dimension 2: Living Space			
I_{15}	Guest room	A spare bedroom is available for guests or as a home office or connection to a guest apartment.	(48, 50, 107–111)
I_{16}	Building energy rating	Energy performance labels (e.g., CO ₂ emissions) are displayed on buildings.	
I_{17}	Attic insulation	Insulation retains indoor temperature and maintains thermal consistency from ceiling to floor.	
I_{18}	Thermal water tanks	Water tanks maintain temperature with high resistance to thermal variation.	
I_{19}	Wall insulation	Includes cavity wall insulation, interior, or exterior insulation.	
I_{20}	Low-maintenance heating systems	Use of alternatives to solid fuels like wood or coal.	
I_{21}	Outdoor storage space	Outdoor space is available for storing recyclables, e.g., used appliances.	
I_{22}	Heating expenditure ratio	Less than 10% of household income is spent on heating.	
I_{23}	Renewable energy sources	Use of renewable energy sources, such as solar panels.	
I_{24}	House orientation and daylighting	Good building orientation ensures sunny rooms during the day.	
I_{25}	Accessible heating controls	Heating systems are easy to control, including temperature settings.	
I_{26}	Roll-in shower accessibility	Ground floor bathrooms allow for installation of roll-in showers.	
I_{27}	Bathroom proximity	Bathroom is located adjacent to the main or master bedroom.	
I_{28}	Indoor natural light	Use of windows, skylights, etc., effectively brings natural light indoors.	
I_{29}	Comfortable ambient temperature	Living room should maintain 21 °C, and other rooms 18 °C, per WHO recommendations.	
I_{30}	Soundproofing and quietness	The residence has good sound insulation and a quiet surrounding environment.	
I_{31}	Color contrast	Color contrast is used in home interiors (e.g., doors, frames, walls) for better visibility.	
Dimension 3: Age-Friendly Design			
I_{32}	Equitable use	Design is usable by people with diverse abilities.	(52, 90–92, 121, 122)
I_{33}	Flexibility in use	Accommodates a wide range of preferences and abilities without adjustments.	
I_{34}	Simple and intuitive use	Design is easy to understand and operate with clear visual instructions.	
I_{35}	Perceptible feedback	Design provides necessary information effectively through high contrast and auditory cues.	
I_{36}	Tolerant of error	Layouts minimize risks or consequences of errors and allow for reorientation.	
I_{37}	Low physical effort	Usable efficiently and comfortably with minimal physical exertion.	
I_{38}	Ease of access and use	Items are clearly visible and within reach, suitable for various hand types.	

(Continued)

TABLE 1 (Continued)

Criteria		Description	Reference
Dimension 4: Gerontechnology Application			
I_{39}	Mobility monitoring	Continuously monitors the movements of older adults residents within their home.	(45, 65, 66, 88, 89, 113–118)
I_{40}	Emergency alerts	Sends alerts to family members and care centers during emergencies.	
I_{41}	Fire detection	Triggers secondary alarms when smoke is detected to ensure safety.	
I_{42}	Wandering detection and prevention	Detects when the older adults leave home, counts residents and visitors, and monitors night activity.	
I_{43}	Smart information processing	Analyzes, interprets, and makes decisions based on collected information.	
I_{44}	Heart rate monitoring	Detects irregular heart activity such as cardiac events.	
I_{45}	Fall detection	Uses sensors to detect falls in real-time using threshold algorithms.	
I_{46}	Activity detection	Uses multiple sensors to detect other abnormal activity patterns.	
I_{47}	Emergency button and touchscreen detection	Detects emergency button and touchscreen signals to request help.	
I_{48}	Automatic ambulance calling	Uses voice messages to call for ambulance services.	
I_{49}	Automatic distress messaging	Sends status updates to family and caregivers with requests for help.	
I_{50}	Telehealth for preliminary diagnosis	Enables video calls between older adults and medical staff for remote diagnosis.	
I_{51}	Recording of appointments and medication schedules	Displays doctor-scheduled medical appointments and medication plans.	
I_{52}	Medical consultation via video call	Enables remote video consultation with personal physicians.	
I_{53}	Social interaction via video call	Allows video calls between older adults and family or friends.	
I_{54}	Daily and medication schedule tracking	Displays reminders for daily activities and medications set by family members.	
I_{55}	Touchscreen control panel	Activates all necessary communication systems through an interface, with programmable functionalities.	

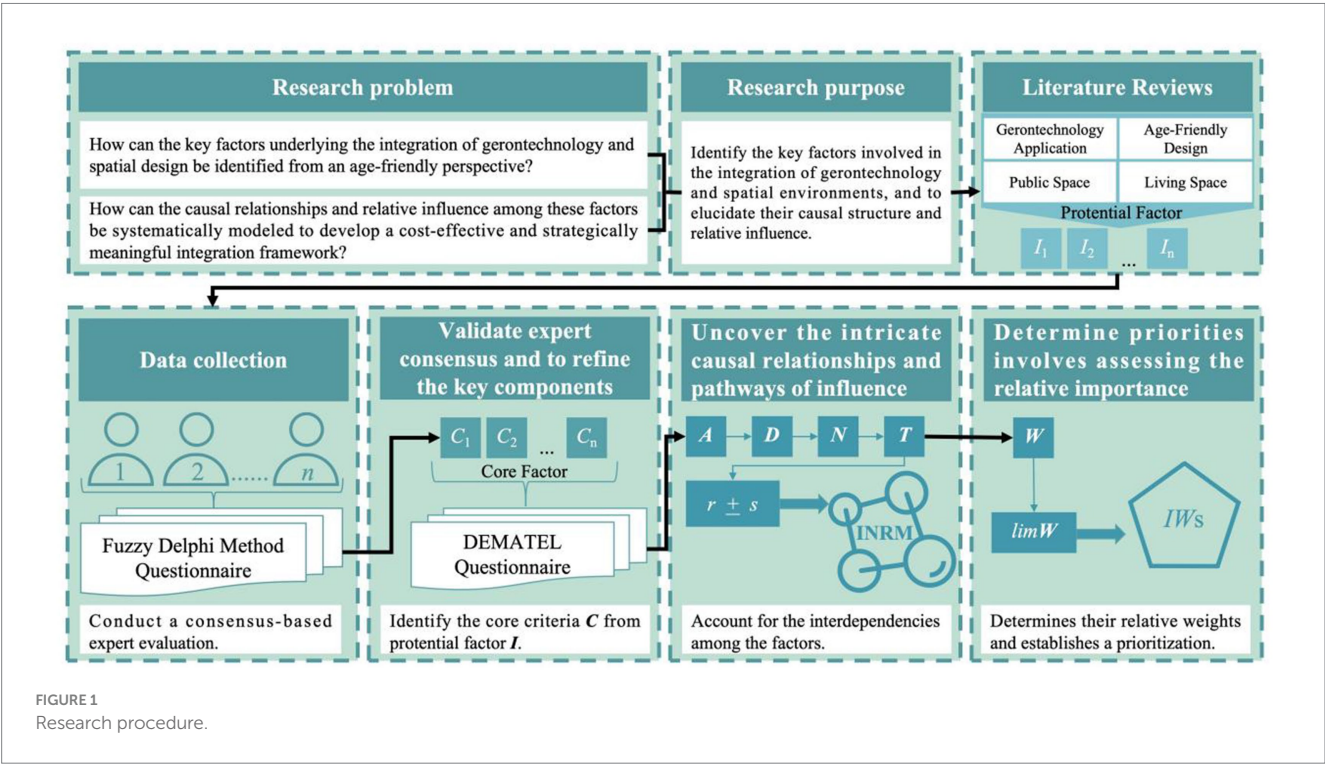


FIGURE 1
Research procedure.

should be verified, and the necessity of including additional experts should be evaluated.

$$\text{Average gap-ratio on consensus(\%)} = \frac{1}{n(n-1)} \sum_{t=1}^n \sum_{j=1}^n \left(\left| a_{ij}^N - a_{ij}^{N-1} \right| a_{ij}^N \right) \times 100\% \quad (3)$$

Step 2: Normalization for Constructing the Direct Influence Matrix D .

In this step, the initial average matrix A is normalized using Equations 4, 5 to construct the direct influence matrix D .

$$s = \max \left(\max_{1 \leq i \leq n} \sum_{j=1}^n A_{ij}, \max_{1 \leq j \leq n} \sum_{i=1}^n A_{ij} \right) \quad (4)$$

$$D = \frac{A}{s} \quad (5)$$

Step 3: Derivation of the Total Influence Matrix T .

After the convergence of the Markov process, the total influence matrix T is derived, where I denotes the identity matrix obtained after an infinite number of influence interactions, as shown in Equation 6.

$$\begin{aligned} T &= N + N^2 + N^3 + \dots + N^k \\ &= N \left(I + N + N^2 + \dots + N^{k-1} \right) \left[(I - N)(I - N)^{-1} \right] \\ &= N \left(I - N^k \right) (I - N)^{-1} \\ &= N \left(I - N \right)^{-1}, \text{ when } k \rightarrow \infty, N^k = [0]_{n \times n} \end{aligned} \quad (6)$$

Step 4: Identification of Interrelationships Among Indicators.

The analysis of interrelationships involves computing four key metrics for each indicator: influence r , receptivity c , causality m , and centrality p . Specifically, the influence score quantifies the extent to which a given indicator affects others, and is represented as a vector, as shown in Equation 7.

$$r = (r_i)_{n \times 1} = \left[\sum_{j=1}^n t_{ij} \right]_{n \times 1} = (r_1, \dots, r_i, \dots, r_n) \quad (7)$$

The receptivity score quantifies the extent to which a given indicator is influenced by others. As shown in Equation 8, it is represented in vector c form in this study.

$$c = (c_i)_{n \times 1} = (c_j)'_{1 \times n} = \left[\sum_{i=1}^n t_{ij} \right]_{1 \times n} = (c_1, \dots, c_j, \dots, c_n)' \quad (8)$$

The causality score is defined as the difference between the extent to which an indicator influences others and the extent to which it is influenced. The result is represented as a vector m . As shown in Equation 9, a positive m_i value indicates that the indicator acts as a driving factor, while a negative m_i value implies that it functions as a resulting factor.

$$m = m_i = r_i - c_i \quad (9)$$

The centrality score, as shown in Equation 10, is computed as the sum of an indicator's influence and receptivity scores, and is represented in vector p , reflecting the relative importance of the indicator.

$$p = p_i = r_i + c_i \quad (10)$$

Step 5: Construction of the Influence Network-Relation Map (INRM).

Based on the calculated causality (m) and centrality (p) scores, the INRM is generated to visualize the causal interrelationships and relative importance of the indicators.

Step 6: Construction of the Total Influence Matrix for Criteria and Dimensions.

As shown in Equation 11, the total influence matrix for the criteria $T_c = [t_c^{ij}]_{n \times n'}$, comprising n criteria is established. Similarly, the total influence matrix for the dimensions $T_D = [t_D^{ij}]_{m \times m'}$, comprising m dimensions clustered under the criteria is also constructed.

$$\begin{array}{c} \begin{matrix} D_1 & D_j & D_m \\ c_{11} \dots c_{1n_1} \dots c_{j1} \dots c_{jn_j} \dots c_{m1} \dots c_{mm_m} \end{matrix} \\ \begin{matrix} c_{11} \\ c_{12} \\ \vdots \\ c_{1n_1} \\ \vdots \\ c_{j1} \\ \vdots \\ c_{j2} \\ \vdots \\ c_{jn_j} \\ \vdots \\ c_{m1} \\ c_{m2} \\ \vdots \\ c_{mm_m} \end{matrix} \begin{bmatrix} T_c^{11} & \dots & T_c^{1j} & \dots & T_c^{1m} \\ \vdots & & \vdots & & \vdots \\ T_c^{i1} & \dots & T_c^{ij} & \dots & T_c^{im} \\ \vdots & & \vdots & & \vdots \\ T_c^{m1} & \dots & T_c^{mj} & \dots & T_c^{mm} \end{bmatrix} \end{array} \quad (11)$$

3.1.3 DANP

When making decisions, decision-makers not only consider the interrelationships among various factors but also attach importance to their prioritization. Determining such priorities involves assessing the relative importance of each factor. To address this need, Saaty (33) proposed the Analytic Network Process (ANP), a systematic comparison approach. ANP extends the Analytic Hierarchy Process (AHP) by accounting for interdependencies among factors, thereby overcoming the AHP's assumption of factor independence and offering decision-makers a more realistic basis for decision-making (80).

To date, the integration of the ANP with DEMATEL commonly referred to as the DANP method, has been widely applied in various fields, including smart city development (81, 82), improvements in smart homes (83), green open spaces for the older adults (84), public open space design (79), and housing for healthy older adults (85). Therefore, this study further applies the DANP method to account for the interdependence among factors, identify their relative influence weights, and determine the prioritization of factors related to age-friendly spaces, thereby providing a scientific basis for decision-making.

Step 1: Normalization of the Total Influence Matrix T_c within Each Dimension.

To derive the unweighted supermatrix, the total influence matrix T_c is normalized within each dimension using Equation 12.

$$\begin{array}{c}
 \begin{array}{ccc}
 D_1 & D_j & D_n \\
 c_{11} \dots c_{1m_1} & \dots & c_{j1} \dots c_{jm_j} & \dots & c_{n1} \dots c_{nm_n}
 \end{array} \\
 \begin{array}{c}
 c_{11} \\
 c_{12} \\
 \vdots \\
 c_{1m_1} \\
 c_{21} \\
 c_{22} \\
 \vdots \\
 c_{jm_j} \\
 \vdots \\
 c_{n1} \\
 c_{n2} \\
 \vdots \\
 c_{nm_n}
 \end{array}
 \end{array}
 \begin{bmatrix}
 T_c^{\alpha 11} & \dots & T_c^{\alpha 1j} & \dots & T_c^{\alpha 1n} \\
 \vdots & & \vdots & & \vdots \\
 T_c^{\alpha i1} & \dots & T_c^{\alpha ij} & \dots & T_c^{\alpha in} \\
 \vdots & & \vdots & & \vdots \\
 T_c^{\alpha n1} & \dots & T_c^{\alpha nj} & \dots & T_c^{\alpha nn}
 \end{bmatrix}
 \quad (12)$$

The total influence matrix normalized by dimension is denoted as T_c^α . As illustrated by dimension $T_c^{\alpha 11}$, this matrix $T_c^{\alpha mm}$ can be derived using Equations 13, 14.

$$\begin{aligned}
 t_i^{11} &= \sum_{j=1}^{m_1} t_{ij}^{11}, i=1,2,\dots,m_1 \quad (13) \\
 T_c^{\alpha 11} &= \begin{bmatrix} \frac{t_{c11}^{11}}{t_{c1}^{11}} & \dots & \frac{t_{c1j}^{11}}{t_{c1}^{11}} & \dots & \frac{t_{c1m_1}^{11}}{t_{c1}^{11}} \\ \vdots & & \vdots & & \vdots \\ \frac{t_{ci1}^{11}}{t_{ci}^{11}} & \dots & \frac{t_{cij}^{11}}{t_{ci}^{11}} & \dots & \frac{t_{cim_1}^{11}}{t_{ci}^{11}} \\ \vdots & & \vdots & & \vdots \\ \frac{t_{cm_11}^{11}}{t_{cm_1}^{11}} & \dots & \frac{t_{cm_1j}^{11}}{t_{cm_1}^{11}} & \dots & \frac{t_{cm_1m_1}^{11}}{t_{cm_1}^{11}} \end{bmatrix} \\
 &= \begin{bmatrix} t_{c11}^{\alpha 11} & \dots & t_{c1j}^{\alpha 11} & \dots & t_{c1m_1}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ t_{ci1}^{\alpha 11} & \dots & t_{cij}^{\alpha 11} & \dots & t_{cim_1}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ t_{cm_11}^{\alpha 11} & \dots & t_{cm_1j}^{\alpha 11} & \dots & t_{cm_1m_1}^{\alpha 11} \end{bmatrix} \quad (14)
 \end{aligned}$$

Step 2: Construction of the Unweighted Supermatrix W^α .

Following the pairwise comparison mechanism of ANP, the total influence matrix normalized by dimension is transposed using Equation 15 to construct the unweighted supermatrix W^α , denoted as $W^\alpha = (T_c^\alpha)'$.

$$\begin{array}{c}
 \begin{array}{ccc}
 D_1 & D_i & D_m \\
 c_{11} \dots c_{1m_1} & \dots & c_{i1} \dots c_{im_j} & \dots & c_{n1} \dots c_{nm_n}
 \end{array} \\
 \begin{array}{c}
 c_{11} \\
 c_{12} \\
 \vdots \\
 c_{1m_1} \\
 c_{21} \\
 c_{22} \\
 \vdots \\
 c_{jm_j} \\
 \vdots \\
 c_{n1} \\
 c_{n2} \\
 \vdots \\
 c_{nm_n}
 \end{array}
 \end{array}
 \begin{bmatrix}
 W^{11} & \dots & W^{i1} & \dots & W^{n1} \\
 \vdots & & \vdots & & \vdots \\
 W^{1j} & \dots & W^{ij} & \dots & W^{nj} \\
 \vdots & & \vdots & & \vdots \\
 W^{1n} & \dots & W^{in} & \dots & W^{nn}
 \end{bmatrix}
 \quad (15)$$

Step 3: Calculation of the Total Influence Matrix Normalized by Dimension T_D .

Using Equations 16, 17, the total influence matrix T_D is divided by the dimensional sum matrix d_i , which yields the dimension-normalized total influence matrix T_D^α .

$$d_i = \sum_{j=1}^m t_{ij}, i=1,2,\dots,m \quad (16)$$

$$\begin{aligned}
 T_D^\alpha &= \begin{bmatrix} \frac{t_{11}}{d_1} & \dots & \frac{t_{1j}}{d_1} & \dots & \frac{t_{1m}}{d_1} \\ \vdots & & \vdots & & \vdots \\ \frac{t_{i1}}{d_i} & \dots & \frac{t_{ij}}{d_i} & \dots & \frac{t_{im}}{d_i} \\ \vdots & & \vdots & & \vdots \\ \frac{t_{m1}}{d_m} & \dots & \frac{t_{mj}}{d_m} & \dots & \frac{t_{mm}}{d_m} \end{bmatrix} \\
 &= \begin{bmatrix} t_{11}^{\alpha D} & \dots & t_{1j}^{\alpha D} & \dots & t_{1m}^{\alpha D} \\ \vdots & & \vdots & & \vdots \\ t_{i1}^{\alpha D} & \dots & t_{ij}^{\alpha D} & \dots & t_{im}^{\alpha D} \\ \vdots & & \vdots & & \vdots \\ t_{m1}^{\alpha D} & \dots & t_{mj}^{\alpha D} & \dots & t_{mm}^{\alpha D} \end{bmatrix} \quad (17)
 \end{aligned}$$

Step 4: Calculation of the Weighted Supermatrix W .

Using Equation 18, the dimension-normalized total influence matrix T_D^α is multiplied by the unweighted supermatrix W^α to derive the weighted supermatrix W .

$$W = T_D^\alpha W^\alpha = \begin{bmatrix} t_{11}^{\alpha D} \times W^{11} & \dots & t_{i1}^{\alpha D} \times W^{i1} & \dots & t_{m1}^{\alpha D} \times W^{m1} \\ \vdots & & \vdots & & \vdots \\ t_{1j}^{\alpha D} \times W^{1j} & \dots & t_{ij}^{\alpha D} \times W^{ij} & \dots & t_{mj}^{\alpha D} \times W^{mj} \\ \vdots & & \vdots & & \vdots \\ t_{1m}^{\alpha D} \times W^{1m} & \dots & t_{im}^{\alpha D} \times W^{im} & \dots & t_{mm}^{\alpha D} \times W^{mm} \end{bmatrix} \quad (18)$$

Step 5: Computation of the Limiting Weighted Supermatrix W and Weight Derivation.

According to Equation 19, the weighted supermatrix W is iteratively raised to the power of z until convergence is reached, resulting in the limiting weighted supermatrix. The local weight of each dimension is obtained by summing the weights of all its associated criteria. Subsequently, the global weight of each criterion is divided by the local weight of its corresponding dimension to obtain the criterion's local weight.

$$\lim_{z \rightarrow \infty} (W^z) \quad (19)$$

3.2 Data collection

To obtain reliable and context-relevant expert input, this study invited participants from diverse domains, including government, industry, and academia, thereby ensuring a broad range of expertise and disciplinary perspectives (see Table 2). Experts were invited to

participate in this study through online channels (SMS and Google Forms). To minimize dominance bias, each expert was required to complete the questionnaire independently. All expert information and questionnaire data collected during the process were accessible solely to the researchers for analysis. Data collection was carried out in two rounds:

The first round survey of this study was conducted in March 2025, during which six experts with practical experience were invited to complete the FDM questionnaire (Appendix 1). In the questionnaire, experts were asked to assess the importance of 55 potential factors identified in prior literature, with the aim of identifying the key factors underlying the integration of Gerontechnology and spatial contexts. Each expert held a senior management position and possessed either more than ten years of professional experience or a doctoral degree. Their areas of expertise included government planning, higher education, Gerontechnology, and consumer services, thereby ensuring their ability to assess key factors from both macro-level policy and industry practice perspectives.

The second round survey of this study was conducted between April and May 2025. To improve the robustness and objectivity of the findings, experts from both academia and industry were invited to complete the DEMATEL questionnaire (Appendix 2). Experts were asked to conduct pairwise comparisons of the key factors identified in the first round, in order to further elucidate their interrelationships and relative importance. After collecting responses from 12 experts, the researchers synthesized the results and assessed their consistency using Equation 3. Panel consensus was considered stable if the consistency level exceeded 95%, in which case no additional experts were required (79, 86). In the second round, the consensus index for all 12 experts exceeded 95% (99.75, 99.51, 99.46, 99.47%). These results indicate that the panel demonstrated reliable representativeness and consensus, thereby concluding the data collection process.

Overall, the 12 experts invited in this round comprised both early career scholars and senior practitioners, and most of them held master's or doctoral degrees. Their affiliations spanned government agencies, research institutions, technology firms, and the construction sector, providing a combination of extensive research insights and practical experience that enhanced the robustness and objectivity of the study's findings. Notably, several experts specialized in Gerontechnology Applications, the humanities and social sciences, architecture, and public policy. Their interdisciplinary expertise enabled a comprehensive evaluation of the interdependencies among factors, thereby reinforcing the study's systematic understanding of smart age-friendly space planning.

4 Results and discussions

4.1 Key criteria by FDM

Based on the evaluations of six experts using the FDM and the inter-quartile range (IQR) analysis, the threshold for identifying key factors was determined to be 4.44. Consequently, 15 key factors (C_1 – C_{15}) were selected from an initial pool of 55 potential items (I_1 – I_{55}) and classified into four dimensions: Public Space (D_1), Living Space (D_2), Age-Friendly Design (D_3), and Gerontechnology Application (D_4).

Specifically, Public Space dimension included Pavement maintenance and dedication (C_1), Pavement material, width and level (C_2), Separation of bicycles from pavement (C_3) and Outdoor safety enhancement measures (C_4); While Living Space dimension emphasized Barrier-free access to and within buildings (C_5), Environmental design for daylight access and natural ventilation (C_6 to C_8), and Comfortable ambient temperature (C_9). The Age-Friendly Design dimension incorporates Fault-tolerant spatial configuration (C_{10}), which minimizes risks arising from unintentional user actions. Lastly, the Gerontechnology Application dimension focuses on the application of Gerontechnology for emergency and daily support, including emergency notification dispatch (C_{11}), fire and fall detection (C_{12} to C_{13}), Automatic transmission of distress messages (C_{14}), and Appointment and medication schedule reminders (C_{15}). The results are shown as Table 3 and the detailed description of core framework are shown in Table 4.

4.2 Analysis of causal relationships among core criteria through the DEMATEL approach

Through the application of the DEMATEL method, this study further clarifies the core criteria and the interrelationships among them in the context of constructing Age-Friendly and Gerontechnology Applications. A consensus analysis was conducted based on Equation 3, and the resulting consensus indices 99.75, 99.51, 99.46, and 99.47%. All exceeded the 95% threshold, indicating that the expert panel was both highly representative and demonstrated a strong level of agreement (87). Furthermore, based on the average direct influence matrix derived from expert evaluations, the influence relationships between the dimensions and the criteria were calculated individually (see Table 5), leading to the construction of the total influence matrix (Table 6). Subsequently, this matrix was employed to determine the strength and direction of influence among the dimensions and criteria (Table 7), which were then illustrated using the INRM (Figure 2). This figure provides a visual representation of the causal relationships and the corresponding levels of influence among the identified criteria.

The results derived from the INRM indicated that among the four dimensions, Gerontechnology Application (D_4) exhibits the highest overall influence, followed by Age-Friendly Design (D_3), Public Space (D_1), and Living Space (D_2), with a descending order of $D_4 > D_3 > D_1 > D_2$. Within the causal structure, D_4 and D_3 are identified as Cause dimensions, that exert significant influence within the system, whereas D_1 and D_2 are classified as Effect dimensions, being more strongly influenced by the others.

At the criteria level, the INRM reveals the internal causal relationships within each dimension. In Public Space dimension (D_1), Pavement material, width, and level (C_2) exerts the strongest influence, resulting in the ranking order: $C_2 > C_5 > C_3 > C_1 > C_4$. Among these, C_2 , C_5 and C_3 are identified as Cause criteria, while C_1 and C_4 are classified as Effect criteria. In the Living Space dimension (D_2), Orientation and lighting (C_6) is the emerges as the most influential factor, followed by $C_6 > C_8 > C_9 > C_7$. Both C_6 and C_8 are identified as Cause criteria. For Age-Friendly Design dimension (D_3), although it includes only one criteria

TABLE 2 Experts background.

No.	Gender	Age	Education	Title	Organization	Seniority (years)
Round 1: FDM						
Exp ₁	M	41–50	PhD	Project Manager	Government Department	>10
Exp ₂	F	41–50	PhD	Marketing Director	Marketing Firm	>10
Exp ₃	M	51–60	PhD	Chief Executive Officer, Professor	Intelligent Technology Company; University	>10
Exp ₄	M	>60	Bachelor	Customer Service Officer	Management Service Company	>10
Exp ₅	M	>60	Bachelor	Manager	Building Management Company	>10
Exp ₆	M	31–40	PhD	Professional Leader	Government Planning Department	3–5
Round 2: DANP						
Exp ₁	M	41–50	Master	Project Manager	Government Department	>10
Exp ₂	M	51–60	Master	Business Unit	Internet Information Organization	>10
Exp ₃	F	51–60	Master	Administrator	Government Department	>10
Exp ₄	M	25–30	PhD	Researcher	Public Policy Institute	3–5
Exp ₅	M	41–50	Master	Vice President	Intelligent Technology Enterprise	>10
Exp ₆	F	25–30	PhD	Research Assistant	School of Architecture	3–5
Exp ₇	M	25–30	Master	Design Assistant	Research Firm	3–5
Exp ₈	F	31–40	PhD	Researcher	School of Humanities and Social Sciences	3–5
Exp ₉	M	25–30	Master	Researcher	Research Institute	3–5
Exp ₁₀	M	41–50	Master	Business Director	Building Supplies Company	>10
Exp ₁₁	M	25–30	Master	Research Assistant	School of Architecture	3–5
Exp ₁₂	M	31–40	PhD	Researcher	Research Institute	3–5

(Fault-tolerant spatial configuration, C_{10}), it should not be underestimated as it is identified as the Cause dimensions. Within the Gerontechnology Application dimension (D_4), Fire detection (C_{12}) demonstrates the highest level of influence among all criteria in the dimension, resulting in the ranking order: $C_{12} > C_{13} > C_{15} > C_{14} > C_{11}$.

4.3 Determination of criteria weights using the DANP method

As shown in Table 8, the Unweighted Supermatrix W^u captures the initial interrelationships among all criteria, prior to normalization and convergence within the DANP procedure. This matrix serves as the computational basis for deriving the final priority weights. Building upon this structure, the DANP analysis quantifies the relative importance of each dimension and its associated criteria (Table 9).

Among the four primary dimensions, Age-Friendly Design (D_3) attained the highest local weight (26.42%), followed by Living Space (D_2) (25.71%), Public Space (D_1) (24.25%), and Gerontechnology Application (D_4) (23.62%). At the criteria level, Fault-tolerant spatial

configuration (C_{10}) emerged as the most influential criteria overall, with a global weight of 26.42%, ranking first among all criteria. The complete ranking of criteria based on global weight is as follows: C_{10} (26.42%) > C_9 (7.18%) > C_8 (6.49%) > C_6 (6.08%) > C_7 (5.95%) > C_{11} (5.49%) > C_{14} (5.38%) > C_4 (5.21%) > C_1 (5.13%) > C_{15} (5.10%) > C_3 (5.03%) > C_5 (4.49%) > C_2 (4.38%) > C_{13} (4.31%) > C_{12} (3.33%).

4.4 Discussion

This study employed a hybrid MCDM model combining FDM and DANP to systematically identify and evaluate the key factors and structural relationships underlying the integration of Gerontechnology and spatial environments from the perspective of older adults. The effect strength in the INRM indicates the driving role of different dimensions within the system's causal network, whereas the weights derived from DANP represent experts' subjective evaluations of decision-making priorities, indicating which dimensions should be prioritized in policy or resource allocation. This study subsequently examines the causal relationships and relative priorities of each factor based on the effect strength ranking in the INRM.

4.4.1 Gerontechnology application

Within the Gerontechnology Application dimension, Fire detection and Fall detection emerge as the most influential criteria, primarily functioning as early warning mechanisms and tools for preliminary incident assessment. Prior research has classified these technologies as essential for addressing adverse events (88). However, they may be insufficient to manage complex or multi-layered emergency scenarios independently.

Among the Gerontechnology Application criteria, Emergency notification dispatch ranks highest in priority and plays a pivotal role during emergency occurrences. The responsiveness of the emergency notification system directly influences the speed at which Automatic transmission of distress messages can relay information to frontline responders such as nurses, caregivers, or call center personnel. This responsiveness is a critical determinant of whether older adults can receive timely assistance in urgent situations. This finding aligns with the results of Melander-Wikman et al. (45), in which older participants expressed fear regarding the inability to obtain timely assistance and conveyed a strong preference for transmitting emergency alerts directly to professionals. Such preferences reflect concerns about unresponsive family members or misplaced external devices, risks that could delay help and ultimately undermine the core objective of Gerontechnology, to safeguard the safety and autonomy of older adults (88).

Beyond emergency response, Appointment and medication schedule reminders also serve a supportive role in facilitating long-term health monitoring within the Gerontechnology Application. Brignell et al. (89) demonstrated that such functions, when integrated as telehealth tools, enhance the effectiveness and efficiency of geriatric care. In particular, within the context of chronic disease management, these systems contribute to improved treatment outcomes and higher levels of patient satisfaction by supporting medication adherence and continuous health tracking.

4.4.2 Age-friendly design

Although the Age-Friendly Design dimension includes only a single criterion (Fault-tolerant spatial configuration), its influence and strategic significance remain substantial. This criterion ranks first in overall priority within the system, thereby constituting a central component of the integrated framework. Fault-tolerant spatial configuration corresponds to the fifth principle of Universal Design, which emphasizes minimizing the risks and negative consequences associated with unintentional or erroneous user actions (90).

These findings underscore for decision-makers that while it is essential to adopt an age-friendly perspective in the integration of technology and spatial design, older adults should not be pathologized or treated as passive recipients of care (91, 92). Older individuals are frequently subjected to stigmatizing stereotypes such as associations with illness, dependency, or social irrelevance, which contribute to internalized shame and significantly hinder their acceptance of Gerontechnology based solutions (93–95). To address this challenge, applying fault-tolerant spatial configuration, a core principle of Universal Design enables the creation of environments that are inherently usable without the need for individual adaptation. This promotes stigma-free accessibility and enhances older adults' willingness to engage with Gerontechnology enhanced spaces (90).

Specifically, fault-tolerant design can be implemented using redundancy and multimodal sensing, whereby motion detectors,

wearable devices, and voice recognition systems can compensate for one another in the event of a malfunction (96). A similar approach has also been applied in fall detection systems, where multi-level confirmation mechanisms help to minimize false alarms (97). By embedding such redundancy and layered safeguards, age-friendly spaces can integrate smart technologies while ensuring resilience and user confidence (16).

4.4.3 Public space

Within the Public Space dimension, Pavement material, width and level, Barrier-free access to and within buildings, and Separation of bicycles from pavement function as key Cause criteria, exerting strong influence within the system. These criteria play a critical role in ensuring that older adults can maintain unimpeded and safe mobility by minimizing the risks posed by physical barriers or suboptimal pavement conditions. The findings highlight the necessity for Public Space design to prioritize infrastructure elements that enhance usability and safety. As noted by Van Hoof et al. (98), pavement material, width, and level are fundamental components influencing not only the physical mobility of older adults but also their perceived safety. Wide and even sidewalks can significantly reduce the risk of falls, whereas uneven or narrow surfaces may become substantial barriers to outdoor movement among the older adults (99). The safety of sidewalks and bicycle lanes significantly impacts the spatial flow within open areas, thereby influencing older adults' ease of movement and overall mobility (100). In particular, Ramírez-Saiz et al. (101) emphasized that the design of shared Public Spaces must account for anticipated user behaviors and safety risks associated with differences in movement speed. Moreover, a growing body of research suggests that the level of physical accessibility within Public Spaces, especially in terms of mobility, directly affects older adults' comfort and ease in social engagement, which in turn shapes their willingness to interact with others in these environments (100, 102, 103).

These findings are consistent with those of Li et al. (104) and Yue et al. (105), which highlight the mediating roles of physical activity and social interaction in the relationship between the built environment and older adults' health outcomes. Notably, although Outdoor safety enhancement measures and Pavement maintenance and dedication are positioned as Effect criteria within the Public Space dimension, their relatively high weights indicate that they rank among the most significant criteria, serving as core elements in ensuring age-friendly spatial design. This supports Turel et al.'s (106) assertion that the success of Public Spaces is not solely contingent upon their physical design and functionality, but also on their sustained vitality, which necessitates careful and ongoing maintenance. Therefore, policymakers should prioritize the long-term quality and safety management of infrastructure related to older adults' mobility, thereby fostering greater willingness to engage in outdoor travel and supporting healthy aging.

4.4.4 Living space

Within the Living Space dimension, Indoor natural light and Orientation and lighting are identified as critical criteria, exerting substantial influence on older adults' comfort and mobility. As individuals age, vision deterioration becomes a progressive issue, with extended adaptation times to sudden light changes and heightened sensitivity to glare (107). Insufficient illumination and color temperature may restrict daily activities and hinder social participation

TABLE 3 Classification of key criteria across core dimensions.

Code	<i>l</i>	<i>m</i>	<i>u</i>	<i>o</i>	Decision (>4.44)	No.
<i>I</i> ₁	3.00	3.96	5.00	3.99	Delete	
<i>I</i> ₂	3.00	3.91	5.00	3.97	Delete	
<i>I</i> ₃	4.00	4.47	5.00	4.49	KEEP	<i>C</i> ₁
<i>I</i> ₄	4.00	4.31	5.00	4.44	KEEP	<i>C</i> ₂
<i>I</i> ₅	3.00	3.96	5.00	3.99	Delete	
<i>I</i> ₆	2.00	3.70	5.00	3.57	Delete	
<i>I</i> ₇	4.00	4.47	5.00	4.49	KEEP	<i>C</i> ₃
<i>I</i> ₈	4.00	4.31	5.00	4.44	KEEP	<i>C</i> ₄
<i>I</i> ₉	4.00	4.00	4.00	4.00	Delete	
<i>I</i> ₁₀	4.00	4.15	5.00	4.38	Delete	
<i>I</i> ₁₁	4.00	4.00	4.00	4.00	Delete	
<i>I</i> ₁₂	3.00	3.81	4.00	3.60	Delete	
<i>I</i> ₁₃	3.00	4.11	5.00	4.04	Delete	
<i>I</i> ₁₄	4.00	4.47	5.00	4.49	KEEP	<i>C</i> ₅
<i>I</i> ₁₅	2.00	3.24	4.00	3.08	Delete	
<i>I</i> ₁₆	1.00	2.40	4.00	2.47	Delete	
<i>I</i> ₁₇	2.00	3.17	4.00	3.06	Delete	
<i>I</i> ₁₈	2.00	3.40	4.00	3.13	Delete	
<i>I</i> ₁₉	2.00	3.17	4.00	3.06	Delete	
<i>I</i> ₂₀	3.00	3.81	4.00	3.60	Delete	
<i>I</i> ₂₁	2.00	3.24	4.00	3.08	Delete	
<i>I</i> ₂₂	1.00	2.70	4.00	2.57	Delete	
<i>I</i> ₂₃	1.00	2.67	5.00	2.89	Delete	
<i>I</i> ₂₄	4.00	4.47	5.00	4.49	KEEP	<i>C</i> ₆
<i>I</i> ₂₅	3.00	4.11	5.00	4.04	Delete	
<i>I</i> ₂₆	4.00	4.64	5.00	4.55	KEEP	<i>C</i> ₇
<i>I</i> ₂₇	3.00	4.11	5.00	4.04	Delete	
<i>I</i> ₂₈	4.00	4.31	5.00	4.44	KEEP	<i>C</i> ₈
<i>I</i> ₂₉	4.00	4.47	5.00	4.49	KEEP	<i>C</i> ₉
<i>I</i> ₃₀	3.00	4.11	5.00	4.04	Delete	
<i>I</i> ₃₁	2.00	3.09	4.00	3.03	Delete	
<i>I</i> ₃₂	3.00	3.63	4.00	3.54	Delete	
<i>I</i> ₃₃	2.00	3.40	4.00	3.13	Delete	
<i>I</i> ₃₄	1.00	3.42	5.00	3.14	Delete	
<i>I</i> ₃₅	3.00	4.26	5.00	4.09	Delete	
<i>I</i> ₃₆	4.00	4.31	5.00	4.44	KEEP	<i>C</i> ₁₀
<i>I</i> ₃₇	3.00	3.96	5.00	3.99	Delete	
<i>I</i> ₃₈	1.00	3.30	5.00	3.10	Delete	
<i>I</i> ₃₉	3.00	4.11	5.00	4.04	Delete	
<i>I</i> ₄₀	4.00	4.64	5.00	4.55	KEEP	<i>C</i> ₁₁
<i>I</i> ₄₁	4.00	4.64	5.00	4.55	KEEP	<i>C</i> ₁₂
<i>I</i> ₄₂	3.00	3.96	5.00	3.99	Delete	
<i>I</i> ₄₃	2.00	3.66	5.00	3.55	Delete	
<i>I</i> ₄₄	3.00	3.91	5.00	3.97	Delete	

(Continued)

TABLE 3 (Continued)

Code	<i>l</i>	<i>m</i>	<i>u</i>	<i>o</i>	Decision (>4.44)	No.
<i>I</i> ₄₅	4.00	4.64	5.00	4.55	KEEP	<i>C</i> ₁₃
<i>I</i> ₄₆	3.00	4.11	5.00	4.04	Delete	
<i>I</i> ₄₇	3.00	4.26	5.00	4.09	Delete	
<i>I</i> ₄₈	3.00	4.26	5.00	4.09	Delete	
<i>I</i> ₄₉	4.00	4.64	5.00	4.55	KEEP	<i>C</i> ₁₄
<i>I</i> ₅₀	3.00	4.11	5.00	4.04	Delete	
<i>I</i> ₅₁	4.00	4.47	5.00	4.49	KEEP	<i>C</i> ₁₅
<i>I</i> ₅₂	2.00	3.30	5.00	3.43	Delete	
<i>I</i> ₅₃	2.00	3.40	4.00	3.13	Delete	
<i>I</i> ₅₄	2.00	3.70	5.00	3.57	Delete	
<i>I</i> ₅₅	1.00	3.30	5.00	3.10	Delete	

The threshold values are Q1: 3.29, Q2:4.00, and Q3:4.44 (Inter quartile range, IQR).

among older adults. Furthermore, Sinoo et al. (108) highlighted that inadequate lighting in corridors, coupled with excessive contrast in brightness levels between corridors and Public Spaces, significantly increases the risk of falls. As such, the design and quality of lighting play a critical role in shaping the living environment, particularly in terms of enhancing safety, mobility, and well-being for older adults.

In contrast, the Roll-in shower is identified as having the lowest influence and priority, suggesting that while its presence is essential, decision-makers can improve and maintain its quality through other design criteria. This aligns with the findings of Aclan et al. (109) and Aplin et al. (110), who note that older adults are reluctant to adopt a “disability bathroom,” a concept often associated with negative stereotypes. Therefore, it is recommended that decision-makers incorporate personalized lighting and home decoration elements in the design of the Roll-in shower, creating an inclusive and non-stigmatized space that aligns with older adults’ preferences.

It is important to note that, despite being classified as an Effect criterion within the Living Space dimension, Comfortable ambient temperature ranks as the second most critical factor in the entire system. Liu et al. (111) highlighted that older adults are particularly sensitive to temperature changes, and extreme temperatures can severely impact both their comfort and health. Therefore, decision-makers should prioritize temperature regulation systems in Living Spaces, ensuring that indoor temperatures are consistently maintained within a comfortable range to prevent health issues caused by overheating or excessive cold, thereby supporting older adults’ functional independence and quality of life at home.

4.4.5 Integration of results across dimensions

Combining the results across all dimensions, this study identifies Gerontechnology Application as the most influential dimension. However, other dimensions including Age-Friendly Design, Living Space, and Public Space are ranked with higher priority than Gerontechnology Application. The results indicate that in practical spatial planning, decision-makers may give priority to Age-Friendly Design (*D*₃) to improve older adults’ everyday experiences, as it carries the highest weight and demonstrates strong policy feasibility. However, to ensure long term policy sustainability, it is essential to enhance the driving role of Gerontechnology Application (*D*₄), as it plays a stronger causal role in the network and can indirectly facilitate improvements

across other dimensions. At the same time, although the application of Gerontechnology can systematically enhance the utility of spatial integration, the Age-Friendly Design remains the most critical requirement in creating environments that truly support older adults’ well-being. This is consistent with recent studies addressing barriers to the implementation of Gerontechnology. For example, Han and Kim (29) emphasized that while modern technology continues to evolve, the integration of technological solutions with spatial environments must first and foremost address the daily needs of older adults, such as facilitating social interactions, mobility, and residential comfort. Without fulfilling these fundamental needs, the benefits of advanced technology for older adults remain limited. Additionally, the results reaffirm the position of Rafferty et al. (30), who argued that spatial constraints and uncertainties in user behavior are fundamental challenges to the successful integration of Gerontechnology in older adults care settings.

It should be noted that, although the Age-Friendly Design dimension includes only one factor after expert decision-making via FDM, it remains a critical factor within the causal structure and is regarded as a core Cause dimension. The results also help explain the adoption gap of Gerontechnology among older users. Pal et al. (112) observed that prior research on the integration of Gerontechnology into home environments often prioritized hedonic value as a key design factor. However, they found that “older adults do not perceive smart homes as a source of enjoyment.” This highlights a gap in current mainstream design priorities, which often fail to address the diverse health and technological needs of older adults, thereby resulting in lower adoption rates of Gerontechnology in this demographic (44). Therefore, Age-Friendly Design plays a pivotal role in the integration of technology and space, and decision-makers must give due consideration to this crucial aspect when developing age-friendly environments.

5 Conclusion

This study employed an integrated analysis of FDM and DANP to elucidate the causal structures and priority order among the dimensions, thereby developing an integrated framework. This framework addresses the high cost and maintenance challenges in the integration of Gerontechnology with spatial environments highlighted by Rafferty et al. (30). Moreover, the analysis revealed

TABLE 4 Descriptions of core dimensions and associated criteria.

Dimension/criteria		Description	Reference
D₁	Public Space	Public Spaces play a crucial role in fostering social inclusion, mobility, and safety for older adults. The design principles under this dimension emphasize accessibility, visibility, and environmental predictability.	
C ₁	Pavement maintenance and dedication	Pavements should be regularly maintained, free of obstructions, and designated solely for pedestrian use. This ensures safe mobility and reduces the risk of accidents such as trips and falls.	(48, 106)
C ₂	Pavement material, width and level	Walking surfaces should be constructed with non-slip materials and maintain adequate width to accommodate assistive devices like wheelchairs or walkers. Level surfaces with minimized height differences contribute significantly to ease of navigation for mobility-impaired individuals.	(48, 98, 99)
C ₃	Separation of bicycles from pavement	Clearly demarcated zones that segregate pedestrian walkways from cycling lanes or vehicular traffic reduce collision risk and foster a sense of safety for older users in shared urban spaces.	(48, 100)
C ₄	Outdoor safety enhancement measures	Features such as adequate street lighting, surveillance systems, wayfinding signage, and the presence of community patrols create a secure outdoor environment, especially during evening hours or in isolated areas.	(48, 106)
C ₅	Barrier-free access to and within buildings	Buildings should incorporate universally accessible features such as ramps, elevators, tactile guides, handrails, and accessible toilets, ensuring seamless entry, exit, and interior navigation for older adults, thereby supporting independent living.	(48, 102, 103)
D₂	Living Space	The Living Space dimension focuses on the home environment, which is central to aging in place strategies. It prioritizes adaptability, environmental comfort, and future proofing for functional decline.	
C ₆	Orientation and lighting	Proper house orientation enables natural daylighting throughout the day, contributing to circadian rhythm regulation, improved mood, and enhanced visual comfort, especially for those with vision impairment.	(48, 50, 107)
C ₇	Roll-in shower adaptability	Bathrooms should be designed with sufficient space and layout flexibility to accommodate future installation of roll-in showers or transfer equipment, facilitating a seamless transition to accessible hygiene routines as mobility declines.	(48, 50, 109, 110)
C ₈	Indoor natural light access	The use of architectural elements such as large windows and skylights increases natural light penetration, reducing the need for artificial lighting, and supporting visual clarity and spatial awareness in older users.	(48, 50, 107, 108)
C ₉	Comfortable ambient temperature	Indoor temperature should be maintained within the World Health Organization's recommended range (e.g., $\geq 18^{\circ}\text{C}$ in occupied rooms). Proper thermal conditions reduce health risks, particularly cardiovascular complications, and promote residential comfort.	(48, 50, 111)
D₃	Age-Friendly Design	This dimension emphasizes spatial features that align with older adults' behavioral patterns, cognitive needs, and risk profiles. It supports autonomy while minimizing accident potential.	
C ₁₀	Fault-tolerant spatial configuration	Environments should be designed with error tolerance in mind, e.g., wide corridors, looped circulation, intuitive layouts, and clear signage, to allow users to reorient themselves easily and return safely to common areas, even in cases of disorientation or cognitive decline.	(52, 90–92, 121, 122)
D₄	Gerontechnology Application	Spaces integrate gerontechnological solutions to enhance health monitoring, emergency responsiveness, and daily life assistance. This dimension reflects a transition from passive environments to active care systems.	
C ₁₁	Emergency notification dispatch	In the event of emergencies, intelligent systems should automatically notify caregivers or family members, ensuring a rapid response and reducing the severity of medical complications due to delays.	(45, 65, 66, 113, 118)
C ₁₂	Fire detection	Smoke or heat sensors should be integrated into the home infrastructure. Upon detecting fire-related incidents, systems must activate alarms and initiate pre-set emergency communication protocols to alert both the resident and external responders.	(66, 88, 118)
C ₁₃	Fall detection	Wearable or ambient sensors using triaxial accelerometers and 3D motion analysis should be employed to detect falls in real-time. Such systems are vital in providing prompt intervention, particularly for older adults living alone.	(65, 88, 114–116)
C ₁₄	Automatic transmission of distress messages	Systems should be capable of automatically sending alerts, including location and status updates, to designated caregivers, offering essential communication support when the older adults are unable to act independently.	(45, 65, 113, 117)
C ₁₅	Appointment and medication schedule reminders	Smart displays or voice assistants should provide timely reminders about medical appointments and medication schedules set by healthcare providers, thereby enhancing treatment adherence and reducing the burden on caregivers.	(65, 89, 114)

TABLE 5 The average direct-influence relation matrix A.

Dimension	<i>D</i> ₁	<i>D</i> ₂	<i>D</i> ₃	<i>D</i> ₄	
<i>D</i> ₁	0.00	2.50	3.33	2.58	
<i>D</i> ₂	2.25	0.00	3.25	2.75	
<i>D</i> ₃	3.42	3.67	0.00	3.00	
<i>D</i> ₄	3.00	3.17	3.08	0.00	
Criteria					
<i>D</i> ₁	<i>C</i> ₁	<i>C</i> ₂	<i>C</i> ₃	<i>C</i> ₄	<i>C</i> ₅
<i>C</i> ₁	0.00	2.75	3.58	3.33	2.83
<i>C</i> ₂	3.25	0.00	2.67	3.33	2.83
<i>C</i> ₃	3.67	2.67	0.00	3.67	2.58
<i>C</i> ₄	2.92	2.58	3.33	0.00	2.75
<i>C</i> ₅	3.00	2.58	2.83	2.83	0.00
<i>D</i> ₂	<i>C</i> ₆	<i>C</i> ₇	<i>C</i> ₈	<i>C</i> ₉	
<i>C</i> ₆	0.00	1.33	3.42	2.67	
<i>C</i> ₇	1.25	0.00	1.00	1.17	
<i>C</i> ₈	2.25	2.25	0.00	2.83	
<i>C</i> ₉	1.75	1.75	1.50	0.00	
<i>D</i> ₄	<i>C</i> ₁₁	<i>C</i> ₁₂	<i>C</i> ₁₃	<i>C</i> ₁₄	<i>C</i> ₁₅
<i>C</i> ₁₁	0.00	2.42	2.83	3.50	2.83
<i>C</i> ₁₂	2.75	0.00	1.25	3.08	2.42
<i>C</i> ₁₃	3.67	1.00	0.00	3.33	3.67
<i>C</i> ₁₄	3.50	2.42	2.58	0.00	3.42
<i>C</i> ₁₅	3.58	1.50	3.00	3.25	0.00

that Gerontechnology Application was the most influential dimension, whereas Age-Friendly Design emerged as the most critical dimension. These findings echo the observations of Peek et al. (16), who noted that the compatibility and adaptability of Gerontechnology with the environment are key factors influencing older adults' willingness to adopt Gerontechnology. By combining causal and weight analyzes, this study offers a more cost effective and strategically oriented framework for the integration of Gerontechnology and spatial environments.

5.1 Theoretical implications

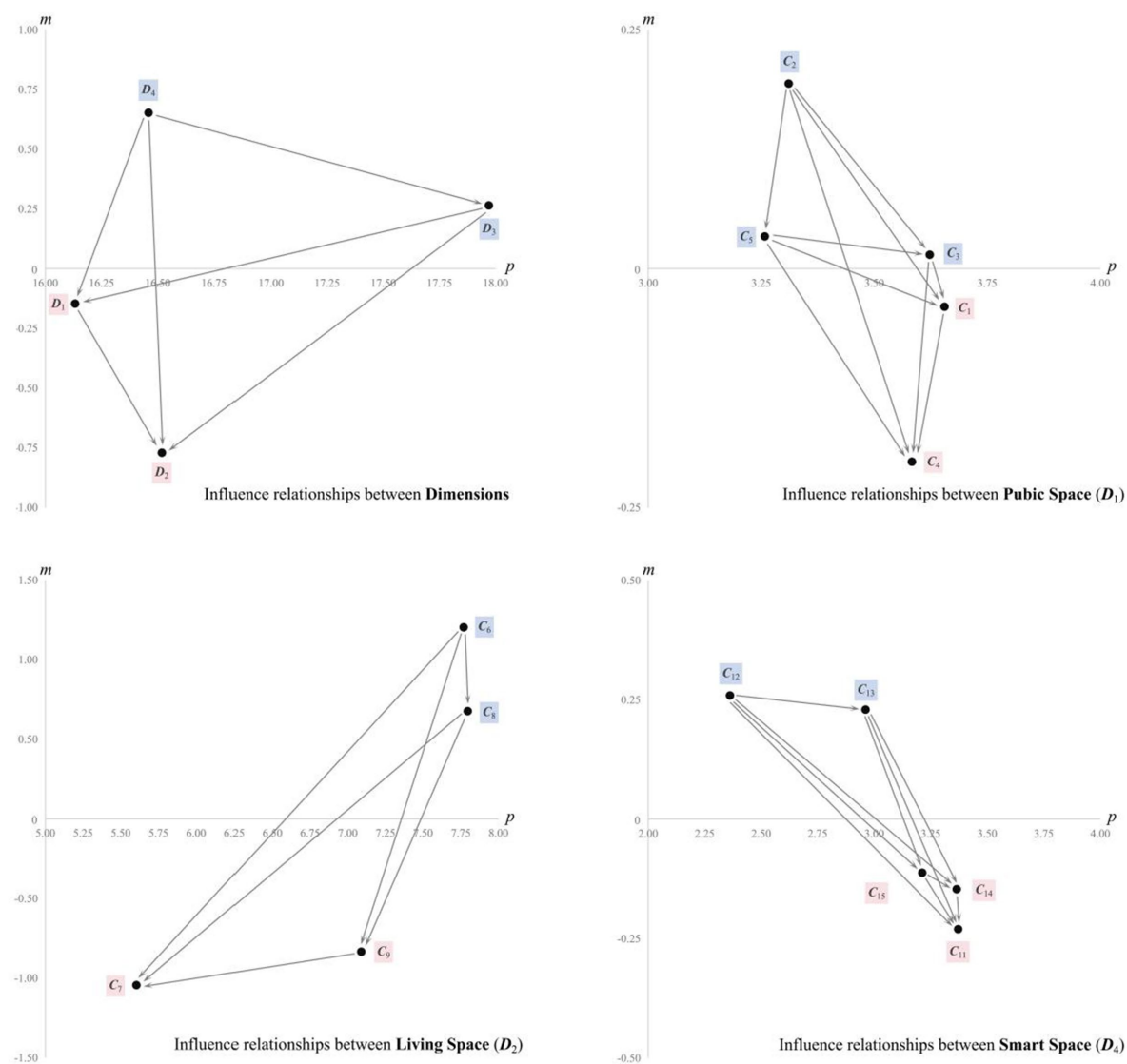
The theoretical contribution of this study lies in the development of a multi-criteria decision-making (MCDM) evaluation framework that integrates Gerontechnology with spatial environments and systematically elucidates the interdependencies and causal relationships among key factors. The findings not only broaden the scope of Gerontechnology but also fosters an interdisciplinary dialogue between environmental psychology, human factors engineering, and facilities management. For instance, the concept of Fault-tolerant spatial configuration in this study transcends the traditional focus on system stability in industrial products and is extended to encompass the spatial system's ability to support older adults' fundamental life functions and dignity. This theoretical implication, which translates technological resilience into caregiving

TABLE 6 The total influence matrix T.

Dimension	<i>D</i> ₁	<i>D</i> ₂	<i>D</i> ₃	<i>D</i> ₄	
<i>D</i> ₁	1.78	2.09	2.19	1.93	
<i>D</i> ₂	1.94	1.87	2.15	1.92	
<i>D</i> ₃	2.28	2.42	2.21	2.20	
<i>D</i> ₄	2.13	2.26	2.31	1.85	
Criteria					
<i>D</i> ₁	<i>C</i> ₁	<i>C</i> ₂	<i>C</i> ₃	<i>C</i> ₄	<i>C</i> ₅
<i>C</i> ₁	0.23	0.36	0.42	0.43	0.37
<i>C</i> ₂	0.41	0.18	0.38	0.42	0.36
<i>C</i> ₃	0.43	0.35	0.23	0.44	0.36
<i>C</i> ₄	0.39	0.33	0.40	0.22	0.35
<i>C</i> ₅	0.38	0.33	0.37	0.38	0.18
<i>D</i> ₂	<i>C</i> ₆	<i>C</i> ₇	<i>C</i> ₈	<i>C</i> ₉	
<i>C</i> ₆	0.87	1.03	1.27	1.32	
<i>C</i> ₇	0.58	0.44	0.60	0.66	
<i>C</i> ₈	1.04	1.05	0.88	1.26	
<i>C</i> ₉	0.79	0.80	0.82	0.72	
<i>D</i> ₄	<i>C</i> ₁₁	<i>C</i> ₁₂	<i>C</i> ₁₃	<i>C</i> ₁₄	<i>C</i> ₁₅
<i>C</i> ₁₁	0.22	0.26	0.32	0.40	0.36
<i>C</i> ₁₂	0.34	0.10	0.22	0.35	0.30
<i>C</i> ₁₃	0.42	0.20	0.17	0.40	0.40
<i>C</i> ₁₄	0.41	0.27	0.32	0.22	0.39
<i>C</i> ₁₅	0.41	0.22	0.33	0.39	0.20

TABLE 7 Strength of influence and causality between evaluation.

	<i>r</i>	<i>s</i>	<i>m</i>	<i>p</i>
<i>D</i> ₁	7.99	8.14	16.13	−0.15
<i>C</i> ₁	1.81	1.85	3.66	−0.04
<i>C</i> ₂	1.75	1.56	3.31	0.19
<i>C</i> ₃	1.82	1.80	3.62	0.01
<i>C</i> ₄	1.69	1.89	3.58	−0.20
<i>C</i> ₅	1.65	1.61	3.26	0.03
<i>D</i> ₂	7.87	8.64	16.52	−0.77
<i>C</i> ₆	4.49	3.28	7.77	1.20
<i>C</i> ₇	2.28	3.32	5.60	−1.04
<i>C</i> ₈	4.24	3.56	7.80	0.68
<i>C</i> ₉	3.13	3.96	7.09	−0.83
<i>D</i> ₃	9.12	8.85	17.97	0.26
<i>C</i> ₁₀	9.12	8.85	17.97	0.26
<i>D</i> ₄	8.56	7.90	16.46	0.65
<i>C</i> ₁₁	1.57	1.80	3.37	−0.23
<i>C</i> ₁₂	1.31	1.05	2.36	0.26
<i>C</i> ₁₃	1.60	1.37	2.96	0.23
<i>C</i> ₁₄	1.61	1.76	3.36	−0.15
<i>C</i> ₁₅	1.55	1.66	3.21	−0.11



No.	Dimension / Criteria	No.	Dimension / Criteria
D_1	Pubic Space	D_3	Age-Friendly Design
C_1	Pavement maintenance and dedication	C_{10}	Fault-tolerant spatial configuration
C_2	Pavement material, width and level	D_4	Gerontechnology Application
C_3	Separation of bicycles from pavement	C_{11}	Emergency notification dispatch
C_4	Outdoor safety enhancement measures	C_{12}	Fire detection
C_5	Barrier-free access to and within buildings	C_{13}	Fall detection
D_2	Living Space	C_{14}	Automatic transmission of distress messages
C_6	Orientation and lighting	C_{15}	Appointment and medication schedule reminders
C_7	Roll-in shower adaptability		
C_8	Indoor natural light access		
C_9	Comfortable ambient temperature		

FIGURE 2
Influence network relationship map (INRM).

TABLE 8 Unweighted supermatrix W^u .

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
C_1	0.13	0.23	0.24	0.23	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_2	0.20	0.11	0.19	0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_3	0.24	0.22	0.13	0.24	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_4	0.24	0.24	0.24	0.13	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_5	0.20	0.21	0.20	0.21	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_6	0.00	0.00	0.00	0.00	0.00	0.19	0.25	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00
C_7	0.00	0.00	0.00	0.00	0.00	0.23	0.19	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00
C_8	0.00	0.00	0.00	0.00	0.00	0.28	0.26	0.21	0.26	0.00	0.00	0.00	0.00	0.00	0.00
C_9	0.00	0.00	0.00	0.00	0.00	0.29	0.29	0.30	0.23	0.00	0.00	0.00	0.00	0.00	0.00
C_{10}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
C_{11}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.26	0.27	0.26	0.27
C_{12}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.08	0.12	0.17	0.14
C_{13}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.17	0.11	0.20	0.22
C_{14}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.26	0.25	0.13	0.25
C_{15}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.23	0.25	0.24	0.13

TABLE 9 Calculated local and global weights for all criteria.

Dimensions	Local weight	Criteria	Local weight	Global weight	Rank
D_1	24.25%	C_1	21.15%	5.13%	9
		C_2	18.07%	4.38%	13
		C_3	20.75%	5.03%	11
		C_4	21.49%	5.21%	8
		C_5	18.53%	4.49%	12
D_2	25.71%	C_6	23.66%	6.08%	4
		C_7	23.14%	5.95%	5
		C_8	25.26%	6.49%	3
		C_9	27.94%	7.18%	2
D_3	26.42%	C_{10}	100%	26.42%	1
D_4	23.62%	C_{11}	23.25%	5.49%	6
		C_{12}	14.12%	3.33%	15
		C_{13}	18.26%	4.31%	14
		C_{14}	22.77%	5.38%	7
		C_{15}	21.59%	5.10%	10

potential, provides a fresh interpretative lens for understanding Gerontechnology and its integration with spatial environments.

Furthermore, through the application of FDM and DANP, this study extends the theoretical application of MCDM models to the field of aging space research. While MCDM has traditionally been used in industries such as engineering and manufacturing, this study introduces it to the domain of Gerontechnology and spatial design, demonstrating its capability to capture causal relationships and weightings between dimensions, thus providing a more explanatory and decision-supporting theoretical tool. By employing expert knowledge and experience for holistic judgments and system modeling, this study underscores the

theoretical value and cost effectiveness of expert input during the exploratory phase of developing evaluation systems. This approach enables the systematic consideration of the evaluation system's structure, grounded in experts' professional knowledge and extensive practical experience, prior to the involvement of end users, thereby laying a foundation for subsequent empirical research. Moreover, this study incorporates multidimensional factors into the evaluation framework for Age-Friendly Design. This not only enriches the theoretical foundations of Gerontechnology Applications within spatial environments but also offers an operational model to inform the future development of human-centered smart space theories.

5.2 Managerial implications

This study employed collective expert judgments and multi-criteria decision-making methods to develop an evaluation framework for the application of Gerontechnology in spatial environments that is both operational and policy relevant. Particularly in contexts of limited resources or during the early stages of research, framework construction based on expert judgments can provide planning guidance and help avoid delays associated with large-scale field investigations. Furthermore, the results can serve as a reference for policymakers in promoting Gerontechnology initiatives and for the construction sector in implementing smart space standards, thereby fostering the sustainable development of age-friendly cities.

The findings indicate that designing age-friendly spaces cannot rely on single measures but instead requires simultaneously addressing real-time Gerontechnology Applications (e.g., fall detection, emergency alerts, medication reminders) and the structural safety of spatial configurations (e.g., fault-tolerant design of spaces, accessibility in public areas, indoor lighting and temperature control). This multidimensional approach can effectively mitigate risks for older adults in both daily living and emergency contexts, while enhancing their autonomy and sense of security.

Specifically, emergency detection and reporting systems (such as real-time notifications for falls and fires) represent not only technological advancements but also have a decisive impact on the safety and trust of older users. This necessitates that decision-makers integrate the automation and reliability of notification mechanisms into the early stages of spatial planning. The direct linkage to external professional support (e.g., medical units) should be considered a critical facility rather than an optional addition. In the Public Space dimension, pavement maintenance, pedestrian flow separation, and barrier-free facilities have been established as key management measures that enhance older adults' willingness to engage in physical activity and social participation. Facility managers should exceed minimum standards and proactively assess safety risks along mobility paths and in high-traffic areas, regularly updating design configurations to address emerging needs. This same management logic applies to Living Spaces, particularly regarding indoor natural lighting and temperature and humidity regulation. Given that older adults have a lower sensitivity to these environmental factors, environmental control systems must be implemented for fine-tuning and predictive management, reducing discomfort and mitigating the risk of falls.

Additionally, this study highlights that the application of Gerontechnology spans multiple dimensions, including Living Spaces, Public Spaces, and Age-Friendly Design, with significant interdependencies and interactions between these dimensions and their respective criteria. Therefore, the integration of Gerontechnology with Age-Friendly spaces requires collaboration across various sectors. A key consideration for decision-makers across these fields is the necessity of adopting flexible design principles and incorporating fault-tolerant capabilities as the central approach for evaluation and integration, with universal design being one example. If decision-makers prioritize only technical configurations without considering the stability, flexibility, and adaptability of the technology and design, this could lead to a lack of compatibility between the technology and the physical environment, thus reducing the overall effectiveness of the space and diminishing older adults' willingness to adopt the technology.

In other words, decision-makers should move beyond the traditional approach of one-time construction, adopting flexible and upgradeable strategic planning models. For instance, when integrating technologies such as perception devices, remote health monitoring, and fall detection systems into physical spaces, it is essential to consider not only ease of use and scalability but also future maintenance to minimize barriers for older adults. This will ultimately enhance their autonomy and increase the actual usage rates of these technologies. This ensures that the integration of Gerontechnologies and spatial planning can generate true synergies, enabling older adults to live independently for extended periods and supporting the development of a sustainable, human-centered, age-friendly environment.

5.3 Limitation and future research

Although this study integrates Gerontechnology and spatial environments through a hybrid MCDM model to construct a systematic analytical framework, several limitations remain. Although the model effectively reflects the overall trends and priorities of older adults' spatial needs, regional variations may be considerable. The disparities between urban and rural populations are particularly pronounced, not only with respect to infrastructure accessibility but also in terms of attitudes toward technological interventions, perceptions, and lifestyle patterns. Therefore, future research should pursue two complementary directions.

First, the multidimensional nature of Age-Friendly Design can be further delineated into sub-dimensions such as autonomy, dignity, privacy, and social connectedness. Second, greater attention should be devoted to contextual diversity through region-specific and culturally sensitive analyses. Such contextualized adjustments would enhance the framework's responsiveness and practical applicability, ensuring that Gerontechnology design strategies are not only theoretically robust but also adaptable to the lived realities of older adults across diverse environments.

In addition, this study primarily relied on expert experience to establish the indicator system and causal structure. At the early research stage, this approach facilitated the rapid identification of key influencing factors and ensured theoretical as well as professional rigor, thus laying a solid foundation for subsequent fieldwork and participatory research. However, because older adults often face constraints such as time and energy, this study did not directly involve end users (i.e., older adults or caregivers) for empirical validation at this stage. Therefore, future research and practical applications should incorporate user experiences to more comprehensively reflect actual needs and usage contexts.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the studies involving humans. The studies were conducted in accordance with the local

legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

Author contributions

W-QZ: Project administration, Supervision, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. S-MC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. XW: Formal analysis, Methodology, Project administration, Supervision, Validation, Writing – review & editing, Resources.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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