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Spatial Configuration Strategies for Aging Building Design Based on Graph Theory

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SUMMARY: *With the increasingly severe situation of population aging in the society, home care will still dominate the development pattern of elderly care in the future, and the ageing-adapted renovation of the existing buildings has become a necessary link. In this paper, we design a spatial configuration strategy for ageing building design, firstly, we use graph theory algorithm to limit the topology of the plan layout form, and under the influence of the tensor field model constructed by the geometric contour of the site, we realize the evolution of the overall layout of the building plan based on the geometric conditions of the site. Then, based on the BIM digital modal information, the topological relationship of the building interior space is extracted, the optimization design objective of the building interior space is determined, and the derivative design method with the core of the Improved Small Habitat Genetic Algorithm (IPSO-NGA) is applied to carry out the multi-objective optimization, to obtain the best optimization design scheme of the building interior space and to analyze the optimization results to verify them. The experimental results show that the overall index state of the collaborative performance change of the BIM model based on IPSO-NGA is within the controllable range, and the global reliability test curve is smooth, the fluctuation amplitude is small and gentle, and the fluctuation frequency is regular. The method in this paper is able to find the optimal solution for the optimization of space design of the aging building, and the optimal building scheme is more reasonable, with higher application value, which can satisfy the needs of the elderly for home care, and has high research value and market promotion value.*

KEYWORDS: *graph theory; BIM model; small habitat genetic algorithm; multi-objective optimization; aging building*

1 Introduction

Accompanied by the increasingly serious aging situation of the society, the demand for old age is increasing, in order to fully meet the aging market demand, all kinds of aging-friendly design ideas for planning and designing old-age buildings have gained development and use, and have even become the driving force of the old-age industry [1-4]. In this context, how to rationally plan and design ageing-friendly building space to improve the quality of life of the elderly has become an urgent problem [5, 6].

Aging-friendly building space design refers to providing comfortable and convenient living

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and living environments for the elderly in accordance with their physical, psychological and social needs [7, 8]. As the phenomenon of population aging intensifies, more and more elderly people need to seek a more suitable living and aging environment, so the concept of ageing is gradually developed [9, 10]. Architects must have the ability to conduct in-depth research and analysis of the living space required by the elderly in order to truly realize the design of age-friendly buildings [11-13]. The design principles of ageing-friendly buildings include barrier-free design, humanized design and intelligent design. Through barrier-free design, the built environment can adapt to the needs of the elderly so that they can enter and exit the building freely, while humanized design pays attention to the living habits and needs of the elderly and provides a comfortable and convenient living environment [14-17]. Intelligent design provides more convenience for the elderly, monitoring health conditions and reminding medication through intelligent systems, etc. The purpose of the design principles of age-friendly building renovation is to ensure the safety, comfort and convenience of the elderly in the built environment [18-21].

Literature [22] examined the living and living space suitable for the elderly from the perspective of spatial design, and put forward measures suitable for the design of elderly living space through the design points and problems existing in the elderly living space, aiming to create suitable and comfortable aging space for the elderly. Literature [23] explored the architectural design of senior living in the context of aging, analyzed the physiological and psychological problems of the elderly from the actual problems of the elderly, analyzed the problems in the design process and the principles to be followed, and put forward strategies that can improve the level of design. Literature [24] emphasizes the need for welfare facilities for the elderly that are designed to accommodate specific stages of health, and describes nursing homes that provide safe spaces and diverse services to improve the quality of life of the elderly with declining physical, psychological, and social functioning. Literature [25] takes a healthcare building as a research object, analyzes its age-friendly design, and explores the feasibility and design direction of age-friendly buildings, and its purpose is to provide a valuable reference for the renovation of senior buildings. Literature [26] introduced a 3D indoor age-friendly design system based on adaptive genetic algorithm, aiming to create a safe, comfortable and convenient living environment for the elderly, and explored the requirements of aging-friendly design and transformed these requirements into quantifiable design parameters, verifying the potential of the system in providing high-quality design solutions. Literature [27] aims to meet the diversified needs of the elderly, and launches a study on the humanized design of healthcare communities by organizing the real issues in the social context of aging, and elaborates the points of optimal aging design by combining with case studies, which provides references to optimize community services. Literature [28] explored the characteristics of the elderly population and the use needs of the landscape suitable for their age, and based on the sustainable design theory, age-appropriate landscape design, and the use of unique design methods for the design of the aging landscape in the residential area, and the results provide guidance for the design of the residential landscape suitable for the ecological environment of the elderly. Literature [29] discusses the relationship between community environment, needs and behaviors of the elderly, revealing that the needs of elderly residents are complex, they seek safety, comfort, health, social interaction and spiritual wealth, and the existing green space can no longer fully meet their needs.

This paper synthesizes graph theory, tensor field model, BIM model, and improved small habitat genetic algorithm to achieve multi-objective optimal allocation of design space for age-friendly buildings. Graph theory and tensor field model are utilized for topological representation and control of building morphology, and density-based K-means clustering algorithm and adaptive algorithm are utilized to improve the small habitat genetic algorithm at the same time. On this basis, the BIM model is used to extract the spatial topological relationship of building interiors - spatial topological connection diagram, and the derivative design method is used to carry out the multi-objective optimization of the spatial design scheme of the ageing building to obtain the optimal design scheme. Finally, the model is tested for application and the effectiveness of the acquired optimization scheme is analyzed.

2 Multi-objective optimal configuration strategy for space design of aging-adapted buildings

This chapter proposes a multi-objective optimal configuration strategy for spatial design of ageing buildings. First, the topological expression of building morphology is realized based on graph theory, and the tensor field model is used to control the morphology of the ageing building. Second, the building information model (BIM) is constructed to realize the extraction of the topological relationship of the indoor space of the building. Then, the building aging index model is constructed, and the multi-objective optimization of building facilities is realized based on the improved small habitat genetic algorithm (IPSO-NGA). Finally, the best optimized design solution is found through the derivative design method.

2.1 Topological representation of architectural forms based on graph theory

The graph theory of discrete mathematics establishes a node-edge data structure and explores the connectivity between nodes without considering the specific properties of nodes or edges, such as size, position, distance, etc., and is therefore an important basic theory for exploring the structure of systems. The core concept of graph theory is to describe a complex image by looking at a series of points and the relationships between them. Such graphs can be used to represent a specific connection between two objects, which is based on points, and the relationship between two points is represented by a line connecting them, thus making the connection between them more explicit.

Graph theory possesses a great capacity for spatial analysis because it can abstract complex spatial structures into a form that can be observed and understood in an infinite variety of ways, thus allowing research to explore the nature of space in greater depth. In spatial research, the point elements in graph theory refer to the basic spatial elements in a building or a city, while the corridors or passages between the spatial elements can be regarded as the lines in the graph structure, which structure the spatial topology.

2.2 Construction of the tensor field model

The building form is closely related to the current status of the site where it is located, and the contour shape of the site and the important internal nodes will all have an impact on the building geometry. Tensor fields can be constructed from multiple influences within the site to control the direction and shape of the building form and guide the building generation process.

When creating a building, it should be ensured that its angles are consistent with the contour lines of the site. To do this, the study needs to calculate the tensor in space to determine the shape and orientation of the building and to conform to the direction of the current location tensor.

In the control model of the tensor field, a lot of constraint information of the site geometry can be set, including geographic location, natural environment, traffic flow, and axial and center point of the building. In this study, mainly by setting the constraints on the geometric contour of the site, it is investigated that the two-dimensional grid model can be divided into a number of spaces and the tensor value of each vertex is used as a parameter to determine the direction of the vertices of that grid. The tensor direction of each vertex is constantly changing in the field space, and the tensor at any location within the grid is obtained by averaging the direction of the tensor around the vertex.

The study establishes an architectural shape base state topology through a graph, where the nodes in the graph are used as intelligences that can move as a means of generating motion trajectories that fit the field, and the lines in the graph change as the positions of the intelligences change as a means of generating architectural shapes that fit the field.

The tensor t is defined in the study as shown in Figure 1, each tensor t has four directions with an angle of 90° between the four directions each direction is represented by a unit vector.

The basic properties of the tensor t are the following:

The coordinate point $p(x, y)$ is the coordinate of the position of the tensor t in two-dimensional space shown in the figure:

(1) θ is a starting angle, which is determined by the positive direction of the x axis in the diagram. The angle between the vectors is generally 90 degrees, and the starting angles θ are all in the first quadrant, so that the range of values of θ is as follows:

$$\theta \in \left[0, \frac{\pi}{2} r\right) \tag{1}$$

Therefore, the four unit vectors of this tensor can be expressed as follows:

First quadrant:

$$\left\{\lambda \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} | \lambda \neq 0\right\} \tag{2}$$

Second quadrant:

$$\left\{\lambda \begin{pmatrix} \cos\left(\theta + \frac{\pi}{2}\right) \\ \sin\left(\theta + \frac{\pi}{2}\right) \end{pmatrix} | \lambda \neq 0\right\} \tag{3}$$

Quadrant Three:

$$\left\{\lambda \begin{pmatrix} \cos(\theta + \pi) \\ \sin(\theta + \pi) \end{pmatrix} | \lambda \neq 0\right\} \tag{4}$$

Quadrant Four:

$$\left\{\lambda \begin{pmatrix} \cos\left(\theta + \frac{3\pi}{2}\right) \\ \sin\left(\theta + \frac{3\pi}{2}\right) \end{pmatrix} | \lambda \neq 0\right\} \tag{5}$$

If a unit vector $v1$ starts at p, it will follow a straight line parallel to the x axis and the value of θ will increase as its angle increases from 0 to 90°. Once the angle of $v1$ reaches a direction perpendicular to the y axis, it enters the second quadrant, and the vector $v4$, which was originally in quadrant 4, also enters the first quadrant. The value of θ represents the value of the tensor t, so by knowing θ, the angles of the other three vectors can be calculated, and vice versa.

(2) In the first quadrant of the tensor t, its starting angle θ starts at zero. Therefore, when calculating the tensor at each point within the tensor field, its vector v will start from 0 and keep rotating in the direction of 90°, and when it reaches 90°, θ reverts to 0 and repeats the above rotation process again. In this process, x_{vec} and y_{vec}, which characterize the values of the components, will also keep repeating the process of θ becoming larger to 90° until it becomes 0 again, thus realizing the calculation of the tensor of each point in space. Since the tensor t consists of four equally spaced vectors, the following is assumed:

$$\left(\begin{pmatrix} x_{vec} = c\cos N\theta \\ y_{vec} = \sin N\theta \end{pmatrix} \mid N = 4\right) \tag{6}$$

Whichever vector is rotated in the orthogonal directions of the x and y axes, a corresponding formula is generated to represent its trend, both with equation (7), and the values of x_{vec}, y_{vec} in the process are continuously changing:

$$\left(\begin{pmatrix} x_{vec} = 1 \\ y_{vec} = 1 \end{pmatrix} \mid \theta = 0\right) \tag{7}$$

(3) The direction of the tensor at the location points of the site constraints should be consistent with the constraint elements, e.g., after inputting the site contour line constraints, the tensor at these locations is calculated first, and then the eigenvolumes of the generated field space at other locations are calculated.

In computing the tensor t at any point in a two-dimensional space, any of the four vectors can be chosen for the calculation. It is sufficient to know the angle of rotation of any of the vectors with respect to the positive direction of the x axis, and its values of x_{vec} and y_{vec}.

When the point intelligences in the architectural topology move in the tensor field space, their direction is determined by the tensor t at the current position, i.e., starting from the point at the lower right and moving to the current point p, and their subsequent movement will be affected by $t(p)$, which will cause the direction of their movement to change. In Fig. 1, the vector with the smallest angle to the incident direction Vec_{pre} among the four vectors is in the second quadrant, i.e., the vector with the largest value of $Vec_{pre} \cdot Vec_{t(p)}$ is the vector in the second quadrant, and the point intelligences will be guided by this vector to move forward at a fixed speed until they arrive at the target location, and then according to the tensor direction of this location, it will redefine a new traveling path until it completes the whole journey.

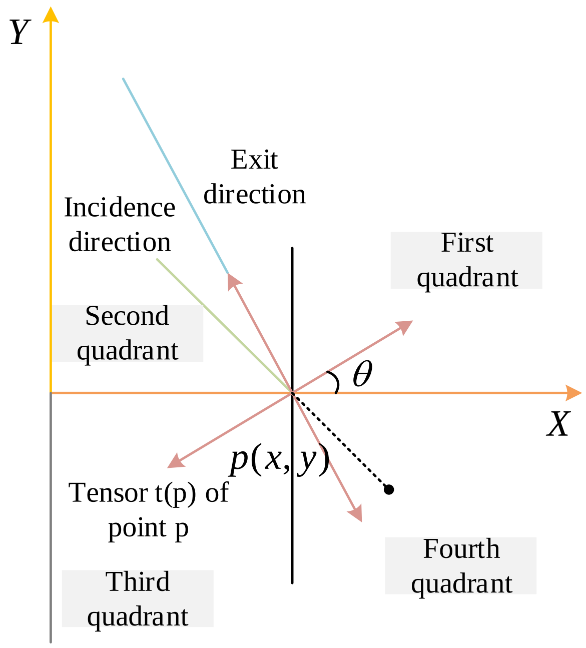


Figure 1: Tensor field model

2.3 BIM-based topological relationship extraction for building interior space

In order to achieve the goal of optimizing the design of the interior space of the ageing building, this section takes the digital modal information of BIM as the basis to design the algorithm for extracting the spatial topological relationship of the interior space of the building to obtain the basic information of the interior space of the building, which lays a solid foundation for the subsequent research to be carried out.

The study adopts Revit software to construct the building information model (BIM) to obtain the digital modal information of the building interior space, which provides certain convenience for its spatial topological relationship extraction. The room in the BIM is regarded as the basic spatial unit, which is also the node in the spatial topological connection graph, and the connectivity state between different basic spatial units is the edge in the spatial topological connection graph, and the entire set of nodes and edges is the spatial topological relationship in the building interior, expressed as:

$$\zeta = \{V(\zeta), E(\zeta)\} \tag{8}$$

In Eq. (8), ζ denotes the spatial topological connectivity graph of the building interior. $V(\zeta)$ denotes the set of nodes of the spatial topological connectivity graph, denoted as $V(\zeta) = \{v_1, v_2, \cdots, v_n\}$, and n denotes the total number of nodes. $E(\zeta)$ denotes the set of edges of a spatial topologically connected graph, denoted as $E(\zeta) = \{e_1, e_2, \cdots, e_m\}$, and m denotes the total number of edges.

It is important to note that there are different definitions for both nodes and edges in spatial topological connected graphs. In particular, the node v_i is defined as follows: when v_i takes a value greater than or equal to 1, it is recognized that v_i represents a room. When v_i takes a value less than 1, it is recognized that v_i denotes an exterior space. The edge e_j is defined as

e_j is recognized as connecting two rooms when e_j takes the value 1. When e_j takes the value of 0, it is recognized that e_j connects the external space to the room.

As shown in Eq. (8), the spatial topological connectivity map is mainly used to describe the connectivity status between the indoor spaces of a building. In order to accurately understand the connectivity of the basic indoor spaces, it is necessary to identify the connectivity element, the door, between each basic space unit. For buildings consisting of multi-story structures, it is necessary not only to analyze the topological relationships of single-story buildings, but also to use elevators or staircases to obtain the connectivity information between individual floors. Although the BIM contains the complete element information of the interior space of the building, in order to express the topological connection information of the interior space of the building more accurately and realistically, it is also necessary to extract the information of its related components. Based on the characteristics of BIM digital modal information, the building interior space component information is determined as shown in Table 1.

Table 1: Information of building interior space components

Component information extraction sequence	Component	Digitized modal information
1	Room	Room ID, location information (X,Y), floor information
2	Door	Door ID, home room ID, owning wall ID, location information (X,Y), floor information
3	Wall	Wall ID, home room ID, location information (X,Y), floor information
4	Elevator	Elevator ID, location information (X,Y,Z), connected floor information
5	Stairs	Stairs ID, location information (X,Y,Z), connected floor information

Based on the digitized modal information of the components shown in Table 1 and the joint definition of nodes and edges of the spatial topological connection graph, the spatial topological relationship extraction algorithm is designed for the interior of the building. The flow of the spatial topological relationship extraction algorithm is shown in Figure 2.

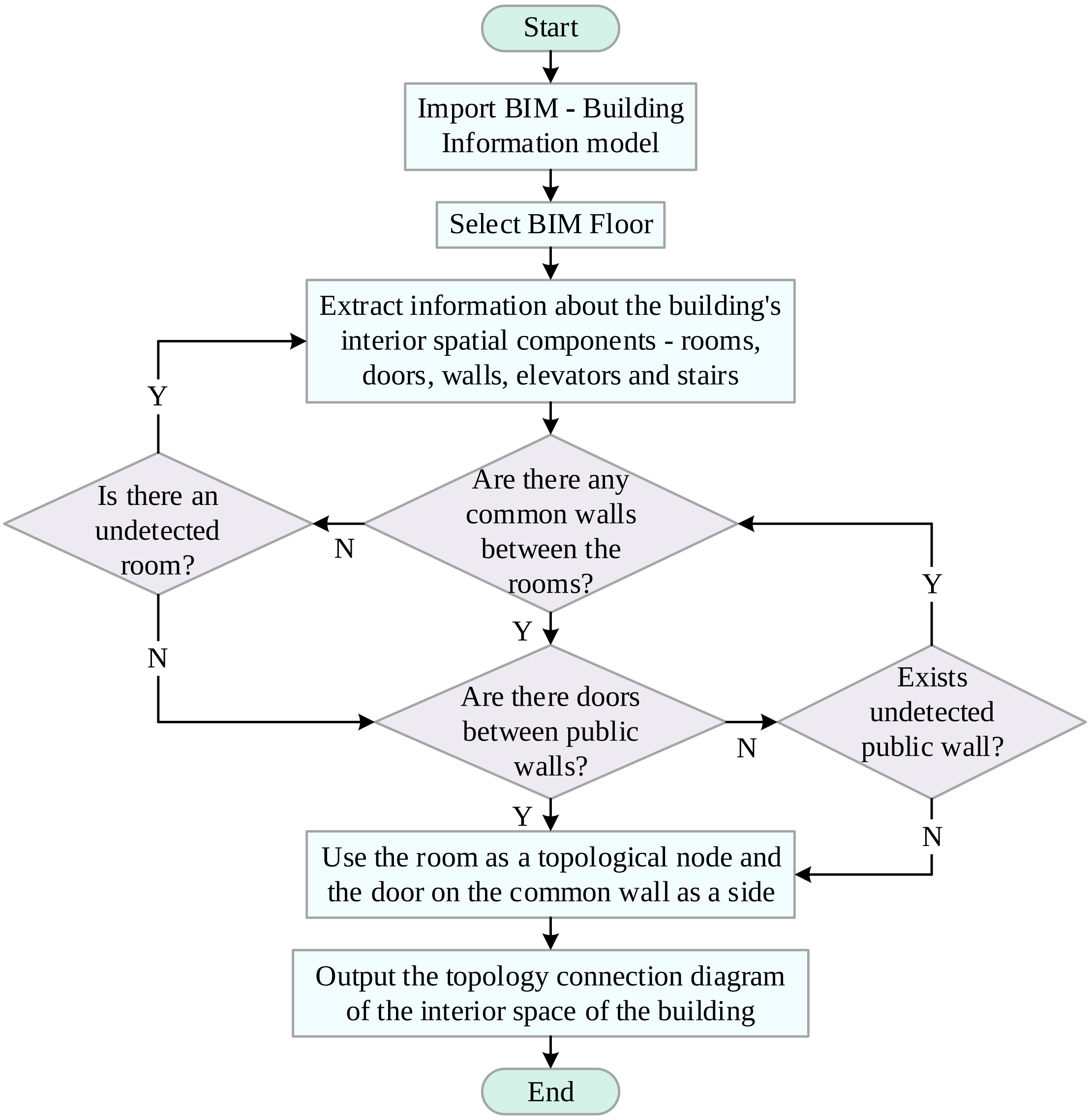


Figure 2: Algorithm flow of spatial topological relationship extraction

The above process completes the illustration and extraction of the topological connection map of the indoor space of the ageing building, which contains the digital modal information of the indoor space components, providing sufficient data support for the subsequent multi-objective optimization design of the indoor space of the ageing building.

2.4 Multi-objective optimization design of aging-adapted building space

Based on the results of building indoor space topological relationship extraction, this section constructs the building aging indicator model and uses the improved small habitat genetic algorithm to optimize the spatial design of aging buildings with multiple objectives.

2.4.1 Modeling of Building Aging Indicators

(1) Selection of model variables

Based on the results of the research and analysis and the index system of the degree of building aging, this paper further constructs the structural equation model on building aging. According to the purpose of the research, the sense of well-being of aging at home is taken as the explanatory variable of the model, and all the six potential variables in the index system of the degree of aging of buildings are taken as the explanatory variables, and each of the potential variables contains multiple observational variables. The relevant variables in the building aging model are shown in Table 2.

Table 2: Relevant variables of the building aging model

Latent variable	Serial number	Observed variable
Home care happiness	Y1	Life satisfaction
	Y2	Health satisfaction
Interior space	X1	Bedroom
	X2	Living/Dining Room
	X3	Balcony
	X4	Kitchen
	X5	Washroom
Public area	X6	Rest area
	X7	Fitness facility
	X8	Road hardening
	X9	Drainage facilities
Barrier free facilities	X10	Height difference treatment
	X11	Vertical traffic
	X12	Anti-slip property
Sensory element	X13	Thermostatic equipment
	X14	Ventilation equipment
	X15	Natural lighting
	X16	Neatness
Health management	X17	Physical disorder
	X18	Audiovisual disturbance
	X19	Chronic disease
Social support	X20	Number of children
	X21	Living arrangement
	X22	Social event

(2) Calculation of Indicator Weights

In order to determine the relative importance of each aging indicator in the model, it is necessary to calculate the weight of each indicator to measure the importance of its impact on the well-being of aging in place. Commonly used weight determination methods include Delphi method, principal component analysis, hierarchical analysis and factor analysis [30]. Factor analysis belongs to the objective assignment method, which can avoid the subjective error of subjective assignment methods such as the Delphi method, and is suitable for the time when there are more index items, which can effectively simplify the system structure and determine the kernel of the system, and at the same time, it can intuitively represent the correlation between each variable, which has advantages compared with the above other methods. The building aging indicator system studied in this paper has more indicators and also needs to explore the correlation between the potential variables, so it is suitable to use factor analysis to calculate the weight of each building aging indicator.

The size of the potential variable weights is determined according to the influence path of each potential variable of the structural model and its overall effect on the influence of well-being. The specific determination method is as follows:

$$W_i = TE_i / \Sigma TE \tag{9}$$

where TE_i is the overall effect of the influence of the i th latent variable on well-being, and W_i is the weight of the i th latent variable.

The weights of the observed variables were assigned based on the factor loadings between each observed and latent variable in the following way:

$$W_j = a_j / \Sigma a_j \tag{10}$$

where a_j is the factor loading coefficient of the j th observed variable, and W_j is the weight of the j th observed variable.

In this paper, the final determination of the weights and sizes of all potential and observed variables of the building aging indicator model are shown in Table 3. Weights of relevant variables of building aging model

Table 3: Weight of relevant variables of building aging model

Latent variable	Overall effect	First order weight	Serial number	Observed variable	Factor loading	Second-order weight
Interior space	0.475	0.210	X1	Bedroom	0.842	0.214
			X2	Living/Dining Room	0.825	0.210
			X3	Balcony	0.673	0.171
			X4	Kitchen	0.764	0.195
			X5	Washroom	0.824	0.210
Public area	0.183	0.081	X6	Rest area	0.733	0.230
			X7	Fitness facility	0.689	0.216
			X8	Road hardening	0.918	0.287
			X9	Drainage facilities	0.851	0.267
Barrier free facilities	0.419	0.185	X10	Height difference treatment	0.796	0.366
			X11	Vertical traffic	0.748	0.344
			X12	Anti-slip property	0.632	0.290
Sensory element	0.492	0.218	X13	Thermostatic equipment	0.827	0.263
			X14	Ventilation equipment	0.856	0.273
			X15	Natural lighting	0.739	0.235
			X16	Neatness	0.719	0.229
Health management	0.397	0.176	X17	Physical disorder	0.852	0.321
			X18	Audiovisual disturbance	0.909	0.342
			X19	Chronic disease	0.896	0.337
Social support	0.293	0.130	X20	Number of children	0.778	0.347
			X21	Living arrangement	0.749	0.334
			X22	Social event	0.715	0.319

2.4.2 Objective function construction

Through the analysis of indoor space components such as rooms, doors, walls, elevators and other factors related to the optimization of building space, the objective function of building cost and residents' happiness in old age is constructed.

(1) Building cost objective function. The building cost objective function includes the prices of various building facilities, which can be expressed as:

$$\min \cos t = \sum_{1 \le j \le n} a_j \times \Delta X_j \tag{11}$$

where: $cost$ denotes the input cost of the building facility, a_j denotes the price of the building facility, and ΔX_j denotes the quantity of the building facility.

(2) Residents' retirement happiness function. When the ratio of building types is set at a certain level, the more building facilities there are, the higher the residents' retirement happiness will be. When in a space of fixed size, the larger the size of building facilities, the number of them will be reduced accordingly, when the residents' daily activity needs can not be satisfied, which leads to a decrease in the sense of old-age happiness. When the size of the building facilities is small, the number of facilities will increase accordingly, and the arrangement will be more dense, which affects the aesthetics of the whole building as well as the environmental planning, etc., and the residents' sense of well-being in old age will also decrease. Comprehensive consideration of the residents' sense of well-being in old age function can be expressed as:

$$\max S = \sum W_i \times (X, +\Delta X_i), \Delta X_j \in E \tag{12}$$

where: S denotes the sense of well-being in old age, W_j denotes the weighted value of the facilities, X_j denotes the number of facilities that have been deployed in the building, and X_j denotes the number of facilities that have been added.

2.4.3 Small Habitat Genetic Algorithm for Optimization of Building Facilities

Using small habitat genetic algorithm [31] to optimize the size of building facilities, due to the genetic algorithm's weak local search ability, this paper improves the genetic algorithm on the basis of the shared function small habitat technique to make the optimization results more reliable.

(1) Adaptive technology to ensure the convergence performance of the algorithm

Although the genetic algorithm can find the optimal individual through a series of operations, but because its calculation parameters are fixed, can not make dynamic adjustments with the changes in the actual environment, the result is that the accuracy of the optimal solution cannot meet the requirements. After analysis, it can be seen that the main factor affecting its performance lies in the fact that the individual in the process of adapting to the environment, in order to make itself more adaptable, its genetic behavior has undergone unexpected changes. As a result, adaptive genetic algorithm is proposed. In adaptive genetic algorithm, if the adaptation of the population is in a more concentrated state, the values of the crossover probability P_c and the mutation probability P_m will increase. Conversely, if the fitness of the population is in a more decentralized state, the values of P_c and P_m will decrease. The two parameter probabilities automatically adjust their own values according to the following two equations:

$$P_c = \begin{cases} k_1(f_{\max} - f')/(f_{\max} - f_{\max}), f' \ge f_{\max}, \\ k_2, f' < f_{\max}. \end{cases}$$
$$P_m = \begin{cases} k_3(f_{\max} - f)/(f_{\max} - f_{\max}), f \ge f_{\max}, \\ k_4, f < f_{\max}. \end{cases} \tag{13}$$

where $f_{\max}$ denotes the highest fitness, f_{avc} denotes the mean of fitness, f' denotes the fitness of the individual with the higher fitness among the multiple crossover individuals, f denotes the fitness of the individual that generates variation, and $0 < k_1, k_2, k_3, k_4 \le 1$.

(2) Small Habitat Technique

A sharing function is utilized to correct individual fitness values in a population as a way to ensure population diversity. This sharing function is formed by the combination of coding type difference and fitness difference. Suppose there are two individuals x_i, x_j, the coding value distance between them is $d_1(x_i, x_j)$, and the fitness distance is $d_2(x_i, x_j)$, then the sharing function $S(x_i, x_j)$ can be expressed as:

$$S(x_i,x_j)=\begin{cases}1-d_1(x_i,x_j)/a_1,(d_1<\alpha_1,d_2\ge\alpha_2),\\1-d_2(x_i,x_j)/a_2,(d_1\ge\alpha_1,d_2<\alpha_2),\\1-d_1(x_i,x_j)d_2(x_i,x_j)/a_1\alpha_2,(d_1\ge\alpha_1,d_2\ge\alpha_2),\\0,(\text{other})\end{cases} \tag{14}$$

where α_1, α_2 is the small habitat radius. Incorporate the sharing function into the individual's fitness function to get the modified individual's fitness function:

$$\overline{f}(x_i) = f(x_i) / \sum_{j=1}^{N} S(x_i, x_j) \tag{15}$$

where $f(x_i)$ denotes the modified individual fitness function, $f(x_i)$ denotes the original individual fitness function, and N denotes the total number of individuals.

2.4.4 Improvement of genetic algorithms for small habitats

This subsection uses clustering algorithm and adaptive algorithm to improve the small habitat genetic algorithm at the same time, and the traditional K-means algorithm [32] is improved, so as to combine the improved small habitat genetic algorithm, IPSO-NGA, and the mathematical model of the optimization of the spatial design of the ageing building in order to achieve the improvement of the residents' sense of well-being of old age and other requirements.

(1) Improved K-means algorithm based on density value

Before searching for the optimal solution using the small habitat genetic algorithm, the radius of the small habitat should be determined first. Traditional methods usually use random methods to determine the small habitat radius, which leads to the algorithm with great uncertainty. In this paper, we propose an improved K-means (DK) algorithm based on the density value, which does not need to set the number and radius of the niche, but determines the K value and the center of the initial clustering by the contour coefficient and the density value. After the population is clustered according to the algorithm, each class can be regarded as a small habitat because of its different characteristics, and the crossover and mutation operations are carried out between the small habitats, in order to try to make the sample individuals have better characteristics after the completion of the evolution, to avoid the defects of the traditional algorithm of precocious convergence and to maintain a good diversity of samples.

Let the sample set $Y = \{Y_1, Y_2, ..., Y_N\}$, Y_i is the m-dimensional vector, and N is the number of samples:

$$d_{ij} = \sqrt{(y_{i1} - y_{j1})^2 + \ldots + (y_{im} - y_{jm})^2} \tag{16}$$

$$d_i = \frac{\sum_{j=1}^{N} d_{ij}}{N} \tag{17}$$

The distance between two samples is calculated according to equation (16), and the average distance of the sample Y_i is calculated according to (17).

To solve the first problem, this paper proposes a method to select the initial clustering center. The steps to establish the density index are as follows:

Step1: Calculate the distance d_{ij} between any sample data i and j.

Step2: Take each sample point as as the initial clustering center, set a spherical space with r_1 as the radius, calculate the number of samples in each spherical space, and take this value as the density of the point.

Step3: Set the sample data with the highest density as the first initial clustering center.

Step4: Choose an integer r_2 such that it guarantees that $r_2 < r_1$, and statistically select the sample data with the next largest density as the second initial clustering center among the data outside of the radius of r_2 of the first initial clustering center point.

Step5: According to the method of Step4, the remaining initial clustering centers are obtained sequentially, and the algorithm ends if $M = K$.

In this paper the contour coefficient is used to optimize the parameter K. The basic steps of DK algorithm are as follows:

Step1: Initialize the population.

Step2: Calculate the total contour coefficient $S(t)$, the formula of contour coefficient is shown in (18):

$$S(i) = \frac{p(i) - q(j)}{\max\{q(i), p(j)\}} \tag{18}$$

where $q(i)$ denotes the average distance between the point i and other points in the class to which the point belongs. $p(i)$ denotes the minimum value of the average distance between the point i and all the points in the class to which the point does not belong. The smaller $q(i)$ is, the more the sample i should be clustered into that cluster, and the larger $p(i)$ is, the less the sample i belongs to the other clusters.

Step3: Calculate the average profile coefficients when taking different K values, and finally select the K value corresponding to the maximum value of the profile coefficient. The contour coefficients corresponding to the K values are calculated separately when different K values are taken, and the contour coefficient value of the K value is the average of the contour coefficients of all the sample points, which is calculated according to Eq. (19):

$$S_t = \frac{1}{N} \sum_{i=1}^{N} S(i) \tag{19}$$

Step4: According to the step of calculating density value, the initial clustering center is obtained.

(2) Adaptive crossover variance probability

In the small habitat genetic algorithm, if the crossover probability and variation probability keep the fixed value unchanged, it may not be able to obtain the optimal extreme point. In order to realize the dynamic adjustment of crossover probability and variance probability, this paper introduces the Sigmoid function, so that the crossover probability p_c is transformed from the initial larger value to a smaller value, and the variance probability p_m is transformed from the initial smaller value to a larger value, and obtains the specific formulas of adaptive crossover probability and adaptive probability as follows:

$$P_c(x) = \frac{1}{1+e^{x-GEN/2}} \times P_c \tag{20}$$

$$P_m(x) = \frac{1}{1+e^{GEN/2-x}} \times P_m \tag{21}$$

where GEN represents the number of evolutionary generations, x represents the first evolution, p_c represents the initialization parameter for the crossover probability, and p_m represents the initialization parameter for the mutation probability.

(3) Elite retention strategy

The small habitat genetic algorithm will constantly carry out genetic operations before reaching the final termination conditions, but there are two steps in the whole genetic operation that can destroy the optimal solution, these two steps are crossover and mutation, because these two operations are random, not necessarily in the evolutionary process to the good direction, it can be to the bad direction of the evolution, when the small habitat genetic is far away from the optimal solution of the objective function will be destroy the optimal solution that has been generated. Therefore, this paper proposes an elite retention strategy and the concept of customized elite repository to retain the elite individuals in the small habitat genetic algorithm.

The elite repository is the set of optimal individuals in each generation of the population. Let the optimal individual in each generation of the population be a_i Let A be the set of elite repositories i.e. $A = \{a_1, a_2, a_3, ..., a_n\}$. The small habitat genetic algorithm saves the optimal solutions in the population produced during each iteration, then compares all the optimal solutions and outputs the final optimal solution. This ensures that the output is the optimal solution in each iteration process, and avoids the optimal solution being damaged by the two operations of crossover and mutation.

Based on the Improved Small Habitat Genetic Algorithm for Spatial Design Optimization of Aging-Ready Buildings (IPSO-NGA), a Difference Particle Swarm Algorithm (DPSO) [33] based on the premise of solving multi-objective optimization is proposed to solve the problem of multi-objective weights computation, and then the Improved K-means Algorithm is used to optimize the small habitats genetic algorithm in initial clustering centers, and at the same time a new algorithm based on the Sigmoid function to construct a new adaptive crossover probability and adaptive variance probability method, which keeps changing with the increase of genetic generations, and can search all the extreme value points of the function more effectively, find the optimal number of building facilities more quickly, and avoid the problem of falling into the local optimal solution caused by entering the stable state more quickly in the process of population evolution. The flow of the improved small habitat genetic algorithm is shown in Figure 3, and the specific implementation steps are as follows:

Step1: Initialize the population, randomly generate M individuals and form an initial population $Q(t)$, and calculate the fitness value $F_i(i = 1, 2, ..., M)$.

Step2: Calculate the fitness of each individual in the $Q(t)$ population and arrange them in descending order, save the first N individuals, take $N=\left[\frac{M}{2}rand\right]+1$, rand is a random number between 0 and 1.

Step3: Classify the population into K clusters and determine the clustering center according to the improved K-means algorithm based on density values.

Step4: Selection operation using elite retention strategy, firstly calculate the fitness value of each individual, then sort the individuals according to their fitness value, secondly select some of the individuals with higher fitness value as the parent, and finally randomly select individuals in each cluster for adaptive crossover and mutation operation to generate new individuals.

Step5: Small habitat elimination operation, calculate the size of the fitness of every two individuals X_i and X_j in each cluster, to add a penalty function to the individual with smaller fitness in every two individuals to make them eliminated faster.

Step6: Calculate the new fitness and memorize the first N individuals.

Step7: Determine whether to terminate the loop, if the termination condition is satisfied, output the result of the algorithm. If the termination condition is not satisfied, continue evolution to update the evolutionary generations and go to Step2.

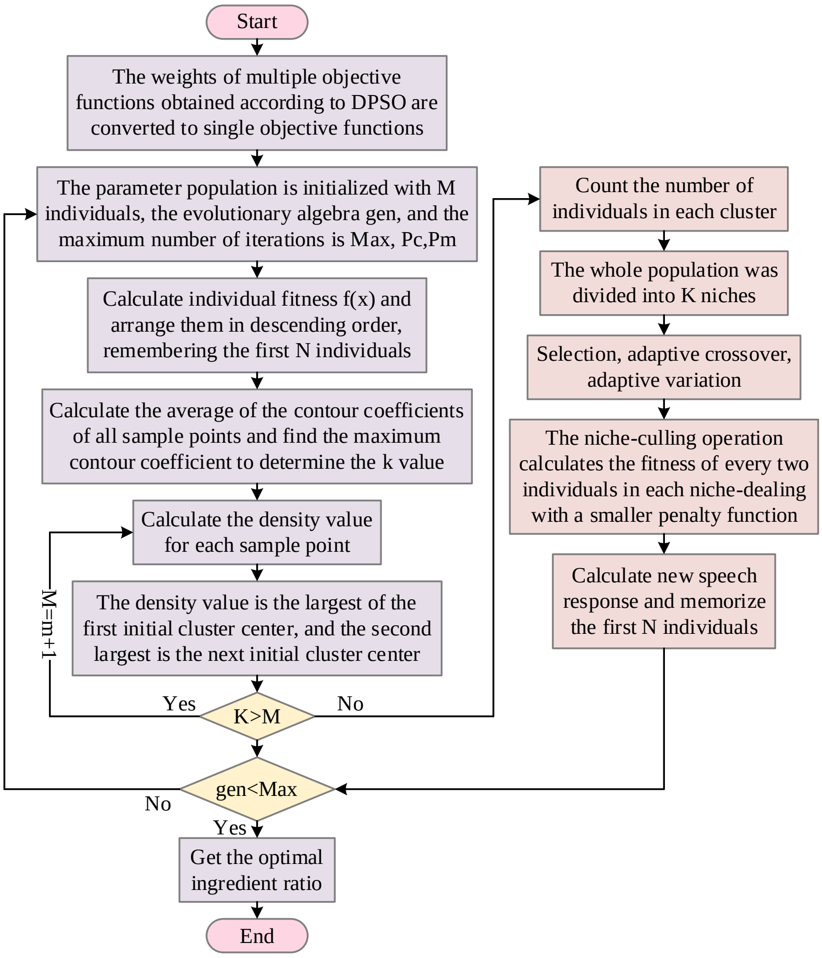


Figure 3: The flow chart of IPSO-NGA

2.5 Acquisition of Optimized Design Solutions for Interior Space of Ageing-Ready Buildings

Based on the extracted indoor spatial topological relationship, i.e., spatial topological connectivity map, and the determined indoor spatial optimization design objectives of the ageing building, the derived design method with the core of the Improved Small Habitat Genetic Algorithm, IPSO-NGA, is applied to obtain the optimal indoor spatial optimization design scheme of the ageing building through continuous iterative operations. Derivative design method is an innovative design method, which generates stochastic solutions with the help of computer technology and iteratively optimizes them to find the best optimized design solution.

The process of obtaining the best optimized design solution for the interior space of an ageing building based on the derivative design method is shown below:

Step1: Load the topological relationship of the indoor space of the building - the spatial topological connection diagram $zeta $, obtain all the digital modal information of the internal construction, generate all the possible indoor space optimization design schemes of the aging building with the help of computer technology, and define the initial particles L_i in the IPSO-NGA algorithm, and the total number is recorded as M .

Step2: According to the determined indoor space optimization design objective of the ageing building, construct the fitness function and add spatial optimization parameters, so as to improve the convergence efficiency of the IPSO-NGA algorithm. The expression of the fitness function is:

$$f(L_i) = \Gamma(L_i) \times \frac{\left[a_1(L_i) + a_2(L_i) + a_3(L_i) - a_4(L_i) - a_5(L_i) - a_6(L_i)\right]}{\mu_0} \tag{22}$$

In the formula, $f(L_i)$ denotes the fitness value of the i th optimal design scheme for the interior space of the ageing building, $\Gamma(L_i)$ denotes the spatial optimization parameter, and μ_0 denotes the normalization factor.

Step3: Calculate the fitness values of all particles based on equation (22), and continuously perform iterative optimization search through selection, crossover and mutation operations to prevent the IPSO-NGA algorithm from falling into local optimality.

Step4: Determine whether the IPSO-NGA algorithm has reached the maximum number of iterations, if it has not been reached, continue to step three. If it has reached the maximum number of iterations, output the optimized design scheme of the interior space of the ageing building corresponding to the maximum adaptability value, i.e., the best optimized design scheme.

By executing the best optimized design scheme obtained above, the optimized design objective of the interior space of the ageing-adapted building can be achieved, and a more reasonable and high-quality interior space environment of the ageing-adapted building can be provided to the user.

3 Analysis and verification of building performance optimization results

3.1 Application test of spatial optimization model for aging-adapted buildings

In order to verify the optimization effect and unify the condition configuration, this section tests the decision-making performance and collaboration performance of BIM models based on the IPSO-NGA algorithm. In order to show the optimization effect more intuitively, two existing optimization methods in the literature are introduced to participate in the test together.

The BIM model samples are imported, and the collaboration weight indexes are collected by the comparison group A, comparison group B verification group, the initial BIM model after normalization is used as the test sample, and the test variable information is randomly configured to ensure that the data obtained is closer to reality. Among them, the collaboration model process information 6000, scale 3000, building facility attribute category is 30, the maximum number of iterations 5, 3 groups of different methods to execute their own optimization scheme, and according to the change of weight indicators to generate the weight change mapping as shown in Fig. 4, (a) ~ (e) respectively, represents the 1st ~ 5th iteration.

According to the changes in the collaboration weight indicators obtained by the three groups of different optimization methods, it can be seen that the changes in the collaboration performance of the BIM models corresponding to the three groups of different methods after five iterations are different, in which the differences are large and need to be analyzed specifically.

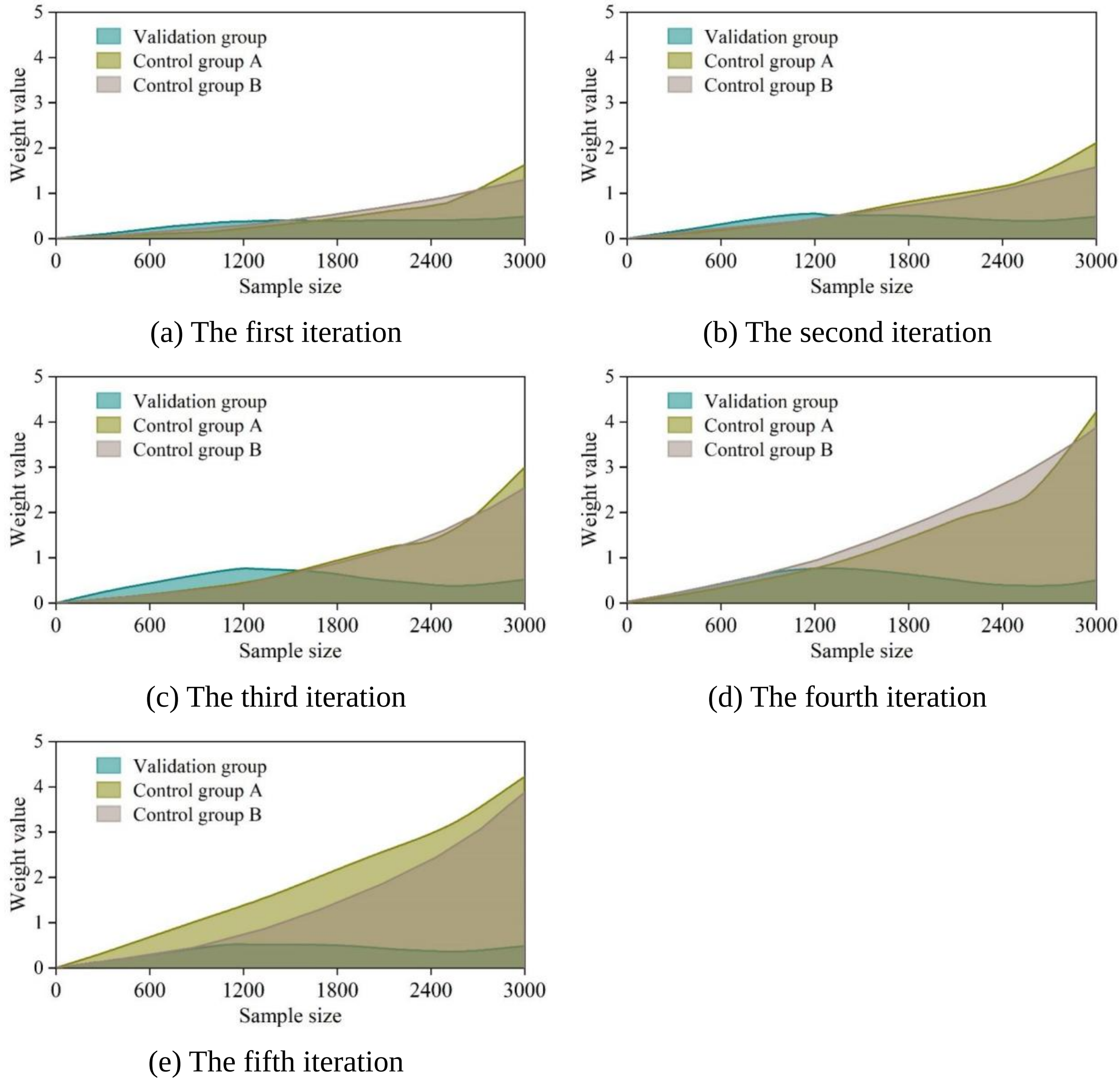
Iteration 1: After the first iteration, the difference between comparison group A and comparison group B and validation group is small, and the late weights between comparison groups A and B are slightly higher than those of validation group, but the overall indicator status is within the controllable range.

The 2nd iteration: when the 2nd iteration is completed, the 3 groups of weight indicators are accompanied by an increase in the number of iterations have increased, in which the comparison group A and comparison group B weight indicators grow significantly faster than the verification group, but the overall growth rate is still within the constraints of the practical application requirements.

The 3rd iteration: after the completion of the 3rd iteration test, the growth of comparison group A and comparison group B has exceeded the constraints, and the growth trend of comparison group A is slightly better than the growth trend of comparison group B. The weight transformation of the validation group has increased in the number of iterations, of which the growth of comparison group A and comparison group B is significantly faster than that of the validation group. At this time, the weight transformation of the validation group enters a smooth state, and there is no substantial and obvious change in the whole.

The 4th iteration: After completing the 4th iteration, the test indicators show that comparison groups A and B enter the peak state of weight change, and the collaboration effect of comparison groups A and B in this state can no longer meet the requirements of practical application. In contrast, the validation group's weight indicator is still in a smooth state.

The 5th iteration: after the completion of the last iteration, the peak values of comparison group A and comparison group B are unchanged, but the stage indicators are improved. According to the determination principle that the larger the weight indicator, the worse the corresponding collaboration performance, it can be determined that the state of the weight indicator of the validation group is more in line with the test requirements.



(a) The first iteration

(b) The second iteration

(c) The third iteration

(d) The fourth iteration

(e) The fifth iteration

Figure 4: Weight change of collaborative performance of BIM models

For the test of decision-making performance, call the decision error model to determine and analyze its decision error, in accordance with 6000 decision information articles, 120 for the mean value of the index for the mean value of the error collation, to get 5 iterations of the 10 groups of decision-making mean deviation as shown in Table 4.

The difference between the values of comparison group A and comparison group B is small, and the overall indicator changes are similar to a high degree, indicating that the decision-making ability of comparison group A and comparison group B is at the same level. The validation group indicators are completely different from the above 2 groups, with smaller values and regular changes, which in terms of the overall state of its corresponding BIM model has a better strategic ability and smaller deviation, and better meets the requirements of practical applications on model deviation.

Table 4: Statistics of decision error test results

Test statistics group	Mean deviation $\Delta\rho$ of control group A	Mean deviation $\Delta\rho$ of control group B	Mean deviation $\Delta\rho$ of verify group
1	0.069	0.058	0.009
2	0.087	0.076	0.009
3	0.094	0.075	0.009
4	0.087	0.068	0.013
5	0.068	0.077	0.015
6	0.087	0.078	0.013
7	0.076	0.078	0.013
8	0.082	0.074	0.014
9	0.078	0.071	0.013
10	0.075	0.066	0.011

In order to ensure the stability of the optimization effect of the proposed method, a global reliability test is conducted. The test is conducted under dynamic data for 960h continuously, and the reliability performance is determined based on the overall performance fluctuation. Among them, the higher the fluctuation frequency and the larger the amplitude, the lower the corresponding reliability. On the contrary, the lower the fluctuation frequency and the smaller the amplitude, the higher the corresponding reliability. The results of the global reliability test are shown in Figure 5.

Observing the fluctuations of the three curves, it can be seen that the fluctuation frequency of the curve of comparison group A is larger than that of the verification group, but smaller than that of comparison group B. And the fluctuation amplitude of comparison group A is slightly smaller than that of comparison group B. Therefore, according to the principle of judgment, it can be determined that the reliability of comparison group A and comparison group B is: comparison group A> comparison group B. On the contrary, the curve of the verification group has smooth global curves, with a small and smooth fluctuation amplitude, and the fluctuation frequency has regularity.

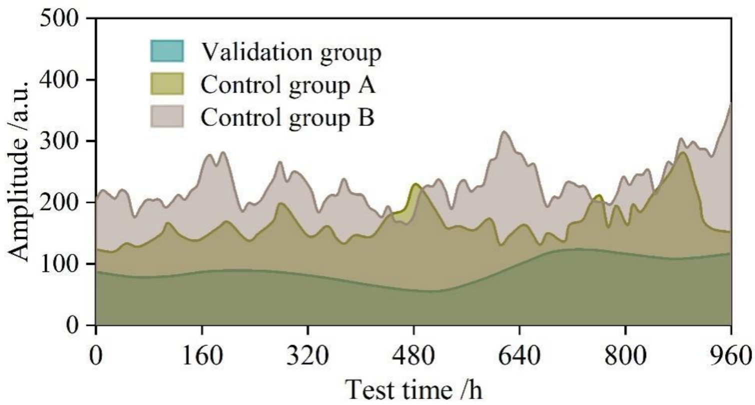


Figure 5: Global reliability test results

3.2 Optimization scheme selection and analysis

In this section, we will visualize the final optimization results and select one of the optimization schemes to make a qualitative analysis.

3.2.1 Pareto Frontier Analysis

The Pareto front is a visualization of the distribution of optimal solutions in the solution space, and is also a tool for the designer to qualitatively select a solution.The Pareto front method provides the designer with enough human freedom to choose the building solution that best meets the designer's expectations from a sufficiently large number of solutions due to the broadness and uniformity of the solution set, which on the one hand takes into account performance-oriented design criteria, and on the other hand ensures that the final design solution is selected in accordance with the designer's expectations. On the one hand, this can take into account the performance design-oriented design guidelines, and on the other hand, it can also ensure that the final selection of design solutions meet the designer's expectations.

The distribution of the final Pareto optimal solution of the ageing building space design optimization project in Cartesian plane coordinates is shown in Fig. 6, with the vertical coordinate as the value of building energy consumption and the horizontal coordinate as the value of thermal comfort APMV. Among them, each small sphere represents a set of spatial parameter values and a set of objective function values, the dark solid purple sphere is the Pareto optimal solution, the light transparent purple sphere is the elite solution, while the rest of the blue sphere represents the historical solution, and the depth of the color represents the number of evolutionary generations, and the darker the color, the closer the number of generations is to the end of evolution. The fold line formed by connecting all the Pareto solutions is the Pareto frontier. From the figure, it can be seen that there is a very obvious Pareto front on the two-dimensional plane. Since the spatial distribution of the optimization objective is itself discrete-valued and inhomogeneous, this results in a Pareto front that is not smooth and unevenly distributed.

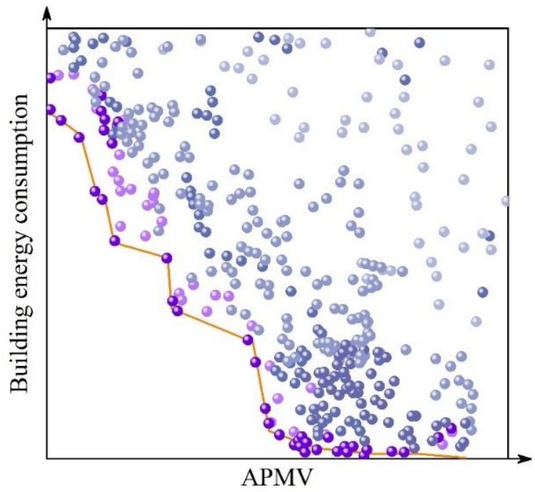


Figure 6: Projection of Pareto frontier on a two-dimensional plane

3.2.2 Optimization scenario analysis

From Fig. 6, we can see that there are 14 sets of optimal solutions on the Pareto front, which are all optimal solutions that take into account the building energy consumption and the indoor thermal comfort of the building. At the early stage of building program design, the designer can choose the solution that best meets the design expectation. In fact, since the scheme design not only needs to consider all kinds of building performance indexes, but also needs to take into account the building site, building façade, flow line form and other design criteria and methods, the designer should combine the actual situation of the scheme with the optimal solution of the Pareto to make secondary adjustments. In this subsection, we will select a solution from the

Pareto front as an example, and analyze the reasonableness of the optimized solution from the perspective of practical application.

One point of the scheme on the Pareto front is selected, which has higher energy consumption and lower APMV value, i.e., better thermal comfort, and the plan combination form of this scheme is shown in Fig. 7(a). In order to make the scheme more holistic, the spatial combination of the scheme is fine-tuned with the same spatial scale, and the fine-tuned scheme is shown in Fig. 7(b). The perspective view of the model of the fine-tuned scheme is shown in Figure 8.

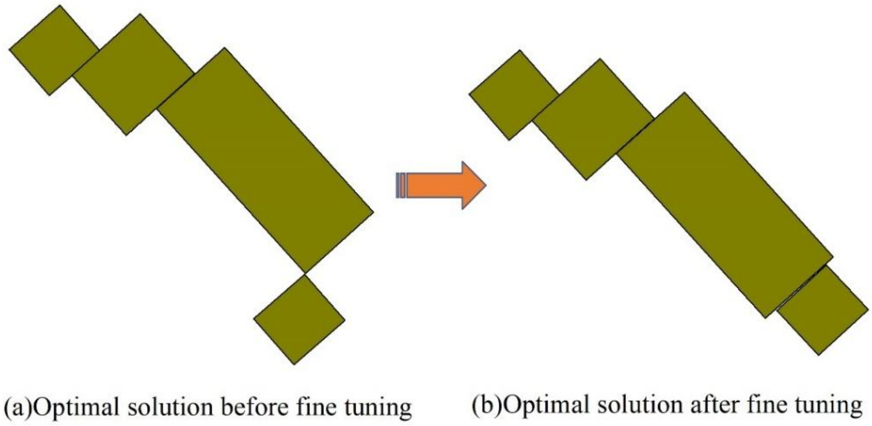


Figure 7: The spatial combination of the scheme is fine-tuned

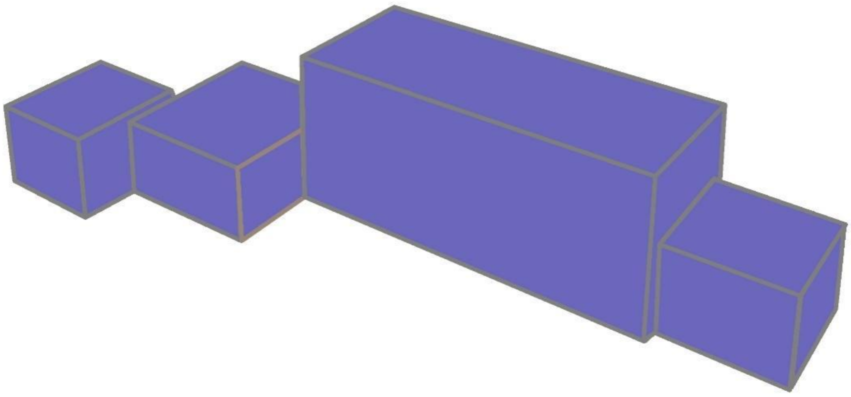
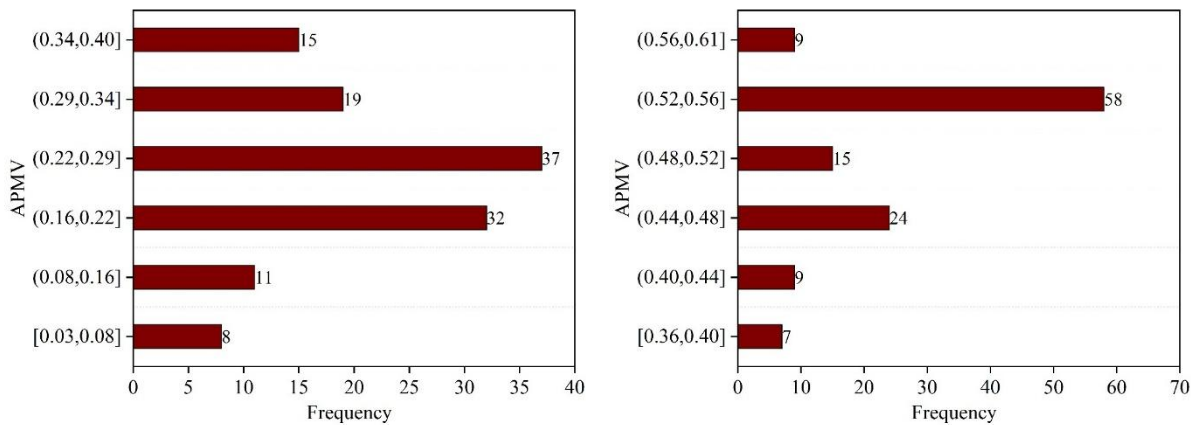


Figure 8: Optimal solution model perspective

By simulating this scenario, the statistics of APMV values for the Multizone thermal model corresponding to this scenario can be obtained as shown in Fig. 9. The horizontal coordinates are the intervals of APMV, and the vertical coordinates are the frequency of Zones with APMV falling in the corresponding intervals, and (a) and (b) denote the statistical results in spring and fall, respectively.

From the distribution graph, it can be seen that the APMV in spring is distributed between [0.03, 0.40] and mainly between [0.16,0.29], accounting for about 56.6%. In the fall, the APMV is distributed between [0.36,0.61], and the proportion distributed between [0.52,0.56] is about 47.5%, which is the main distribution interval. It shows that the optimized scheme can combine the design experience of the designer in order to output a reasonable optimal solution while ensuring that the building performance meets the conditions.



(a) In spring (b) In autumn

Figure 9: APMV distribution inside the building

3.3 General design of housing units

3.3.1 Topological relationship modeling

(1) Predefined topological relationship matrix

Through the preliminary research and analysis as well as field measurements, a comprehensive understanding of the original situation of each part of the space and the design needs of this household type has been obtained. Based on the physical condition of the elderly, the current spatial situation of the living unit, and the design requirements, the topological connection relationship of each space in the sample home suite was optimized, and combined with the research on the design of the two-bedroom suite for the assisted elderly, the predefined topological relationship matrix of each space in the sample home suite was constructed as shown in Fig. 10. The number of topological connections allowed for each space is limited as shown in Table 5.

This topological relationship matrix basically solves several major needs of the elderly:

1) Bedroom connectivity for real-time care.

2) Reasonable planning of living room layout to enhance communication and interaction among the elderly.

3) The design of the return movement line to meet the needs of accessibility.

4) The topology of bathroom and bedroom is adjacent to each other, which is convenient for the elderly to use in daily life.

5) Optimize the indoor flow line to reduce unnecessary movement loss.

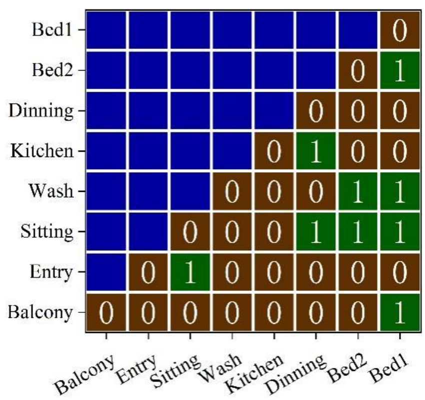


Figure 10: Topological relationship matrix of two-bedroom for the elderly

Table 5: The number of connections allowed in the functional space of the two-room room

Max.	3	4	5	5	4	4	5	6
Min.	1	1	1	1	1	1	1	1
	Balcony	Entry	Sitting	Wash	Kitchen	Dinning	Bed2	Bed1

(2) Generate spatial connection matrix

The above topological relationship matrix is converted to Excel table form, and the template is written in Java language in Processing platform, and after calling the Excel table, the functional topological relationship connection matrix of the corresponding samples' living unit space can be generated as shown in Fig. 11.

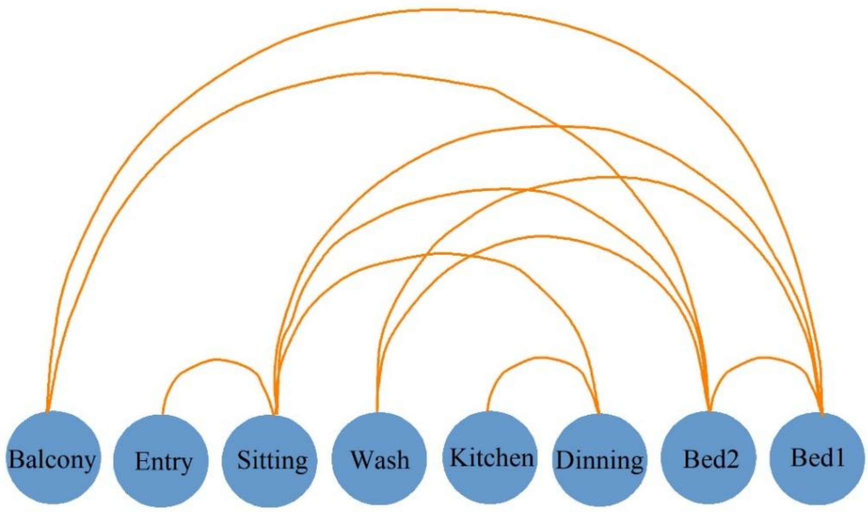


Figure 11: Functional topological connection matrix of the two-room room for the elderly

(3) Generation of topological relationship diagram model

The functional topological connectivity matrix of the sample family mediated elderly two-bedroom apartment derived from the above study was input into the Grasshopper battery pack and automatically generated to obtain an optimized spatial topological relationship graph model as shown in Fig. 12.

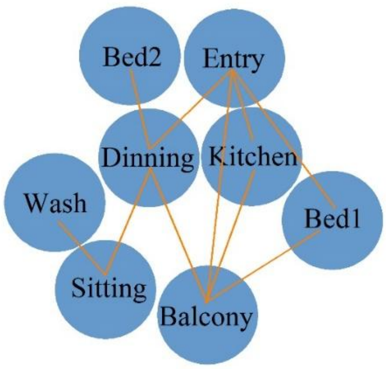


Figure 12: Functional topology diagram model of two-bedroom with auxiliary functions

3.3.2 Layout Plan Model Generation

The functional topological relational map model of the sample home-mediated elderly two-bedroom apartment derived from the above study is used as an input to the Grasshopper battery to limit the building boundaries and entrance locations of the sample living units, and the topology optimization generates the living unit floor plan layout model shown in Fig. 13.

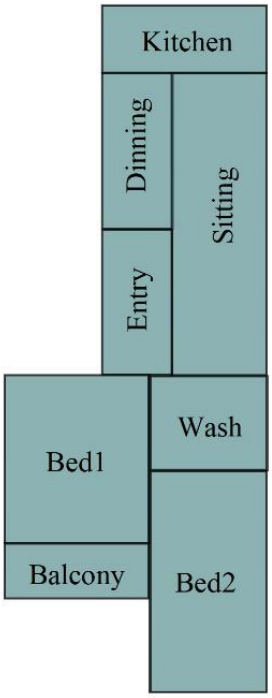


Figure 13: Floor plan model of the two-bedroom with assistant

3.4 Optimization of the spatial layout of ageing-friendly buildings

In the optimization of the spatial layout of the ageing-friendly building, taking into account the mobility difficulties of the elderly, the transitions between the various areas reduce the number of steps and thresholds and keep the ground level. At the same time, the optimized space scale is appropriate, taking into account the auditory characteristics of the elderly. Too large a space will make the elderly feel empty and lonely, while too small a space may make them feel depressed and inconvenienced. Therefore, the optimized living unit reasonably determines the spatial scale and area of each area according to the living habits and physical condition of the elderly. In the optimized spatial layout, emphasis is also placed on barrier-free design, with handrails, non-slip floor tiles, and spacious doorways that are easy for wheelchairs to enter and exit at the nodes of the living units. Emergency call buttons are installed in the bedrooms and living rooms so that the elderly can seek help in case of emergency. The optimized spatial layout is shown in Figure 14.

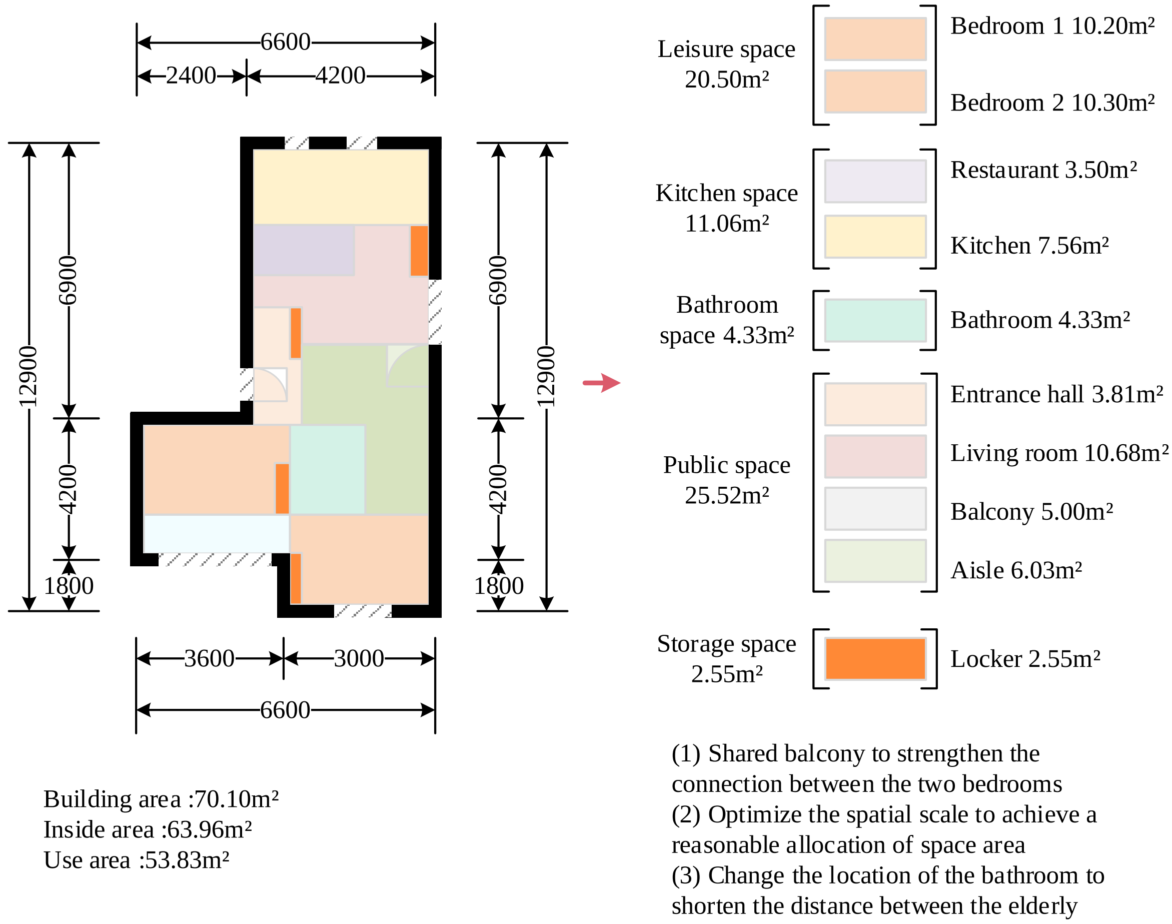


Figure 14: Spatial layout optimization diagram

4 Conclusion

This paper proposes a multi-objective optimization configuration strategy for the design space of aging buildings by combining graph theory, tensor field model, improved small habitat genetic algorithm, and BIM model.

The BIM model based on the improved small habitat genetic algorithm proposed in this paper generates a weight change mapping according to the change of weight indicators when executing the multi-objective optimization of the design space of the aging building design scheme, and the change of the amount of collaborative weight indicators is much smoother, and the state of the weight indicators is always within the controllable range of the look, which has a better collaborative performance.

Through the analysis of the final optimization scheme on the Pareto frontier, the resulting scheme takes into account the building energy consumption and APMV value, with better thermal comfort, which verifies the reasonableness of the final results of the spatial design optimization process of the aging-adapted building proposed in this paper. At the same time, the generative design of the intermediary elderly living unit meets the needs of the elderly for home care and can improve their sense of well-being in old age, thus verifying the feasibility of this research method.

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