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Multi-objective optimization of environmental retrofits in eldercare buildings: A case study in Suzhou

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Abstract

As the aging population continues to grow, ensuring optimal environmental comfort in eldercare facilities has emerged as a critical societal priority. However, existing research on retrofit optimization has predominantly focused on isolated objectives, such as energy or cost reduction, thereby overlooking the complex trade-offs essential for achieving holistic performance in eldercare environments. This study addresses this research gap by proposing a comprehensive, multi-objective optimization framework that simultaneously balances thermal comfort, energy efficiency, and cost-effectiveness. Unlike previous approaches, the proposed methodology integrates architectural design with the evolutionary non-dominated sorting genetic algorithm II, which effectively resolves conflicting objectives and generates Pareto-optimal solutions without the data-intensive demands of conventional machine learning techniques. Focusing on a case study of the Gusu District Shuangta Street Jinfan Community Health Service Center in Suzhou, the research utilizes parametric modeling and the Wallacei plugin in Grasshopper to evaluate over 840,000 retrofit scenarios. The findings reveal tailored strategies – such as the use of Rockwool insulation and low-emissivity glazing – that optimize energy savings while maintaining thermal comfort within budgetary constraints. By bridging architectural innovation with computational optimization, this work not only provides a replicable model for eldercare retrofits but also offers actionable insights for policymakers and practitioners, advocating for interdisciplinary methodologies to meet the evolving demands of aging societies.

Keywords: Eldercare building; Non-dominated sorting genetic algorithm II; Thermal comfort

1. Introduction

1.1. Background

The global demographic landscape is undergoing a significant transformation, characterized by a rapidly increasing aging population.[1] The World Health Organization

projects that the global population aged 60 and older will double by 2050, reaching around 2.1 billion. This demographic change is driving increased demand across various societal systems, with healthcare facilities being a primary focus. Eldercare facilities, in particular, play a crucial role in offering environments that are both comfortable and supportive, designed to address the specific needs of aging individuals.

To proactively address the issue of aging, the Chinese government has proposed a comprehensive elderly care service system to promote social eldercare services, including nursing homes, assisted living centers, community health care centers, and senior housing complexes.[2] However, elderly people in China continue to face the problem of insufficient nursing facilities per capita.[3] To alleviate this shortage, the government is encouraging the renovation and repurposing of abandoned or unoccupied buildings into eldercare facilities. This approach provides a quick and efficient solution to meet growing demand. However, many of these structures were built decades ago without eldercare purposes in mind and often fall short of modern standards for environmental comfort and energy efficiency.

Despite these initiatives, existing retrofit methods exhibit significant shortcomings. Many studies focus solely on isolated metrics such as energy consumption or initial cost reduction, overlooking the complex interdependencies between thermal comfort, cost-effectiveness, and occupant well-being. Furthermore, some approaches employ data-intensive machine learning techniques that require extensive training datasets, yet these methods often fail to capture the nuanced trade-offs essential for creating optimized eldercare environments under specific conditions. This gap underscores the need for a more comprehensive, multi-objective optimization framework that can address the multifaceted challenges of retrofitting buildings for eldercare, thereby ensuring that renovated facilities not only meet modern efficiency standards but also cater to the specific needs of the aging population.

1.2. Literature review

1.2.1. Literature on the retrofit of eldercare building

Retrofitting eldercare buildings presents unique challenges that extend beyond the conventional focus on aging-friendly design. Studies from Europe, such as those conducted in Scandinavian countries, have emphasized passive design strategies, including high-performance insulation, airtightness, and natural ventilation, to improve indoor comfort while minimizing energy demand.[4] Similarly, North American approaches frequently incorporate smart building technologies and data-driven management systems to optimize heating, ventilation, and air conditioning (HVAC) performance.[5,6] Research from Japan has explored the integration of biophilic design and sensory-responsive environments to enhance well-being, demonstrating the importance of psychological and physiological factors in retrofit planning.[7,8] Despite these advancements, a direct application of international methodologies to China presents challenges due to differences in climate, regulatory frameworks, and financial incentives. European retrofits benefit from strong governmental subsidies and stringent energy efficiency regulations. In contrast, retrofit strategies in many parts of China are predominantly driven by budgetary constraints[9] and regulatory mandates,[10] often overlooking comprehensive assessments of occupant well-being. This fragmented approach, observed across various studies, tends to focus on isolated aspects of building performance, such as energy consumption or cost, leading to suboptimal outcomes and missed opportunities for synergistic improvements.[9] Integrating insights from these global studies can provide a more balanced and effective approach tailored to China's unique socio-economic conditions. By aligning China's eldercare retrofit strategies with international best practices, this study highlights the potential to foster more holistic and effective retrofit methodologies. A comparative perspective not only enhances the global relevance of this research but also underscores the need for interdisciplinary, context-specific solutions that prioritize both occupant well-being and long-term sustainability.

1.2.2. Non-dominated sorting genetic algorithm (NSGA) II application

Addressing these shortcomings, this research advocates for a more holistic framework that simultaneously evaluates energy performance, environmental comfort, and cost-effectiveness. To achieve this, we introduce the NSGA II into our methodology. Genetic algorithms like NSGA-II are particularly well-suited for complex multi-objective optimization problems due to their robustness in handling conflicting objectives.[11-14] Compared to other state-of-the-art methods such as NSGA-III or Multi-Objective Evolutionary Algorithm Based on Decomposition (MOEA/D), NSGA-II offers a proven balance between convergence and diversity, making it highly effective in navigating trade-offs among objectives like maximizing thermal comfort while minimizing energy consumption and initial renovation costs.[15] Moreover, the integration of NSGA-II within the Wallacei plugin in Grasshopper streamlines the optimization process, providing a user-friendly interface that facilitates rapid prototyping and fine-tuning of parameters. Unlike NSGA-III and MOEA/D, which often demand more complex parameter

settings and higher computational resources, NSGA-II's iterative evolution process aligns with the non-linear, multidimensional nature of retrofit challenges. This ensures the generation of a diverse set of optimal solutions, represented by a well-distributed Pareto front, where each solution embodies a unique balance of competing objectives. Furthermore, unlike machine learning-based approaches that require extensive training data and may struggle to capture the nuanced interdependencies between thermal comfort, energy usage, and cost, NSGA-II offers a transparent and adaptable framework for decision-making in building retrofits. This not only enhances the technical performance of retrofit strategies but also directly contributes to creating safer and more comfortable environments for elderly residents. Notably, the NSGA-II algorithm has been widely applied in decision-making processes for building retrofit.[12-14]

1.2.3. Thermal comfort metric

The critical importance of thermal comfort in eldercare settings underpins the need for a holistic retrofit approach. Elderly individuals have distinct physiological responses to environmental conditions,[16] making them more vulnerable to temperature fluctuations and other environmental stressors. Poor thermal conditions can significantly affect both the physical and mental well-being of older residents, potentially limiting their social participation and overall quality of life.[16,17] By integrating NSGA-II with a thermal comfort assessment model like predicted mean vote (PMV), this research bridges the gap between societal needs and sustainable innovation. The PMV model, originally proposed by Fanger in the 1970s, estimates thermal comfort by considering six key parameters: air temperature, mean radiant temperature, air velocity, relative humidity, clothing insulation, and metabolic rate.[18]

This research methodology promises more effective and sustainable retrofit strategies, ultimately ensuring that these essential environments meet both operational demands and the well-being requirements of their elderly occupants.

1.3. Methodology

To address these gaps, this study proposes an interdisciplinary approach that integrates architectural design principles with advanced optimization algorithms to develop comprehensive retrofit strategies for eldercare buildings. As shown in Figure 1, this research aims to identify and evaluate multiple retrofit scenarios that balance requirements from environmental comfort, initial cost, and energy efficiency. In this study, the Gusu District Shuangta Street Jinfan Community Health Service

Center serves as the research sample. The sample building is parametrically modeled to simulate various retrofit scenarios, and the Wallacei plugin for Grasshopper is used to prioritize renovation strategies. This multi-objective optimization process considers diverse factors such as thermal comfort, initial cost, and energy consumption, ultimately developing trade-off strategies that can be tailored to different eldercare facilities and individual needs. This study aims to offer a model replicable for future research in related fields, demonstrating the potential of integrating architectural design with computational optimization techniques to support retrofit decision-making.

2. Description of the sample building

The selected case study for this research is a former government administration office located in Suzhou, now repurposed as the Gusu District Shuangta Street Jinfan Community Health Service Center. This building has recently been retrofitted to serve as a community health center specifically designed for neighborhood residents, as shown in Figure 2A. The transformation from an office building to an eldercare facility presents unique challenges and opportunities for optimizing environmental comfort and energy efficiency. The building's original design, intended for administrative functions, did not prioritize the specific needs of elderly occupants, necessitating comprehensive retrofit strategies to create a comfortable and supportive living environment. Furthermore, Suzhou's climate, with hot summers and cold winters, poses additional challenges in achieving optimal indoor environmental conditions.

At present, the building consists of two main functional areas. The first, located on the right side of the building in Figure 2B, is designated for health care. The second, on the left side, serves as the Shuangta Community Administration Office. The healthcare section mainly includes reception, an office, a pharmacy, lobbies, a nursing unit, and an outpatient department. The building is currently the largest and most comprehensive community health service center in the Gusu District, with a total area of 3,000 m². The community administration section includes a reception area, a 24-h office, standard offices, and a storage room. The two sections operate independently, separated by a partition wall in the middle, as indicated in Figure 2B.

3. Measurement of the building

Detailed architectural plans and data from the sample building were collected to create an accurate parametric model, which served as the basis for simulation and analysis. A series of detailed measurements were conducted. These
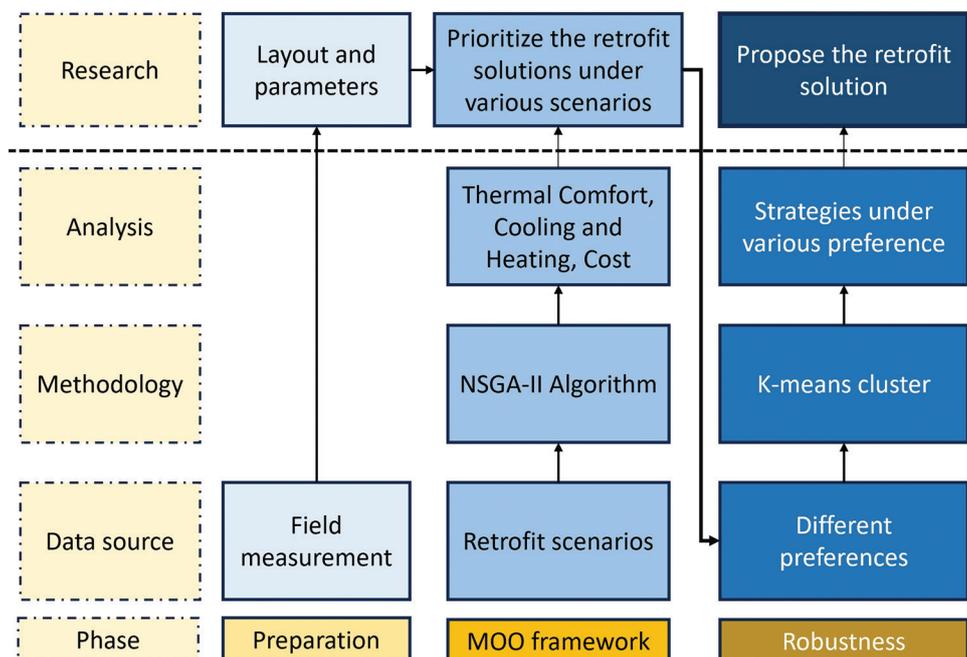
Figure 1. Workflow of the research
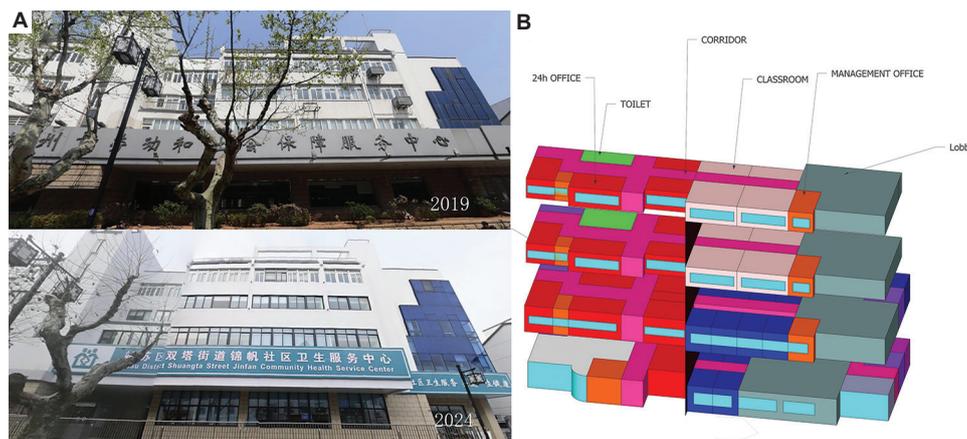Abbreviation: MOO: Multi-objective optimization.

Figure 2. The sample building and room layout. (A) The sample building in 2019 and its current form (source: https://map.baidu.com/). (B) Distribution of room functions.

measurements encompass various aspects of thermal comfort and energy consumption, providing critical data for subsequent simulations and optimization.

The following parameters were measured:
(i) Indoor temperature
    a. Measurement tools: K-type thermocouples and Centertek 309 thermometers were deployed throughout the building to capture temperature variations across different rooms and floors.
    b. Data collected: Indoor temperature readings were recorded at multiple time points during both day and night.

(ii) Thermal properties of the building envelopes
    a. Measurement tools: K-type thermocouples, Centertek 309 thermometer, and a Hukesflux heat flux sensor were used to assess the thermal transmittance of building envelopes.
    b. Data collected: Readings from heat flux sensors and thermocouples were used to calculate the U-values of various building envelope components.

(iii) Energy consumption
    a. Measurement tools: Records from energy meters were collected to monitor heating/cooling energy consumption.

b. Data collected: Data on energy consumption patterns were collected over the summer to capture variations in usage and identify opportunities for energy efficiency improvements.

A summary of the measured thermal properties of the sample building is presented in Table 1.

4. Simulation

The parametric model of the building was simulated using Rhinoceros and Grasshopper to assess different retrofit scenarios. Key variables, such as insulation materials, window designs, HVAC systems, and available insulation options, were adjusted to explore their impact on environmental comfort, cost, and energy efficiency.

4.1. Simulation setup

The setup process is crucial to ensure the accuracy of the simulation. In this study, the setup not only includes the thermal properties of building components but also accounts for internal loads from occupants, lighting, ventilation, and the setpoints of the HVAC system. Overall, the sample building was divided into 10 types of functional spaces. Each space corresponds to a specific building program in the Ladybug tools simulation environment. The program inputs in this study are based on filed questionnaires and relevant building codes in China. The HVAC system was modeled as an ideal air system, without consideration of the Coefficient of Performance. Therefore, the simulated cooling and heating energy consumption represent the calculated cooling and heating loads. Table 2 summarizes the program parameters for each type of space in the simulation.

4.2. Verification of the simulation

Verification of the simulation process is a crucial step to ensure that the computational models accurately reflect the

Table 1. Current conditions and characteristics of the building structure

Component	Structure	Indicators
Exterior wall	Colid brick wall (240 mm) without insulation layer	1.49 W/(m² K)
Window	Single glazing (6 mm) with aluminum frame	5.3 W/(m² K)
Roof	20 mm concrete panel with 10 mm insulation layer	1.21 W/(m² K)
Infiltration	Average air leakage	0.0003 m³/s per m² facade
HVAC	Central air conditioning	$T_{cooling}$=26, $T_{heating}$=18
Shades	None	-

Abbreviations: HVAC: Heating, ventilation, and air conditioning; T: Temperature.

real-world conditions of the sample building. As shown in Figure 3, the verification involves comparing the simulated results of the current condition of the eldercare facility with actual measured data. This comparison helps validate the reliability and accuracy of the simulation models used to develop renovation strategies.

The correlation coefficient between the measured and simulated results is about 0.86. The verification results demonstrate that the simulation models accurately represent the real-world conditions of the sample building. The discrepancies between the simulated and measured data were minimal. This validation confirms the reliability of the simulation process and supports the use of these models in the development and evaluation of retrofit strategies.

4.3. NSGA II with Wallacei

The potential retrofit options explored in this study include insulation materials for the building envelopes, insulation thickness, air seal strips, glazing types, and shading depth. Table 3 lists the selected retrofit options considered in the simulation and optimization process.

The total number of potential retrofit scenarios exceeded 840,000. If each parameter was adjusted for every possible scenario, the estimated simulation period would extend up to 291 days. To reduce computation time and obtain optimization suggestions on the retrofit efficiently, the Wallacei Plugin, based on the NSGA-II algorithm, was implemented in this study. The optimization objectives include thermal comfort, energy consumption, and initial cost in Chinese Yuan (CNY). The PMV-predicted percentage of the dissatisfied model was selected as the thermal comfort model. Typically, the PMV model is used to evaluate the thermal comfort of a conditioned space throughout the entire year. However, during transitional seasons, spring and autumn, the thermal comfort of the exterior environment is generally acceptable for most people. As shown in Figure 4A, the average Universal Thermal Climate Index values in Suzhou during summer and winter are approximately 0.587409 and -0.963889, respectively. Thus, this study focused specifically on optimizing thermal comfort during summer and winter. Within Grasshopper, the Ladybug tools were implemented to evaluate the PMV of interior spaces. The PMV scale ranges from -3 to +3, indicating cold, neutral, and hot thermal sensations, respectively. In the Wallacei component, the objective of thermal comfort was set to minimize the sum of the absolute PMV values during summer and winter. A lower total PMV sum indicates better thermal comfort in these seasons. It is worth mentioning that the energy consumption in this study only includes the energy consumed by the HVAC system.

Table 2. Schedule setup for the simulation

| People	Spare office	Classroom	Corridor	Gate	Biohazard	Office	Patient	Reception	Storage	Toilet
People density (n/m^2)	0.1	0.215	0.0107	0.322	0	0.1	0.215	0.1076	0.1615	0
0	1	0	0.4	0	0	0	0	0	0	0
1	1	0	0.4	0	0	0	0	0	0	0
2	1	0	0.4	0	0	0	0	0	0	0
3	1	0	0.4	0	0	0	0	0	0	0
4	1	0	0.4	0	0	0	0	0	0	0
5	1	0	0.4	0	0	0	0	0	0	0
6	1	0	0.4	0	0	0	0	0	0	0
7	0	0.37	0.4	0	0	1	0	0	0	0
8	0	0.37	0.6	0.005	0	1	0.05	0.05	0.05	0
9	0	0.37	0.6	0.005	0	1	0.05	0.05	0.05	0
10	0	0.19	0.6	0.005	0	1	0.05	0.05	0.05	0
11	0	0.19	0.6	0.005	0	1	0.05	0.05	0.05	0
12	0	0.37	0.6	0.005	0	1	0.05	0.05	0.05	0
13	0	0.37	0.6	0.005	0	1	0.05	0.05	0.05	0
14	0	0.37	0.6	0	0	1	0.05	0.05	0.05	0
15	0	0.37	0.6	0	0	1	0.05	0.05	0.05	0
16	0	0.37	0.4	0	0	1	0.05	0.05	0.05	0
17	0	0.19	0.4	0	0	1	0	0	0	0
18	0	0.19	0.4	0	0	0.5	0	0	0	0
19	0.5	0.19	0.4	0	0	0	0	0	0	0
20	0.5	0	0.4	0	0	0	0	0	0	0
21	0.5	0	0.4	0	0	0	0	0	0	0
22	1	0	0.4	0	0	0	0	0	0	0
23	1	0	0.4	0	0	0	0	0	0	0
Lighting load (W/m^2)	7.965	7.64	7.64	9.04	4.09	7.96	9.79	9.04	4.52	6.78
Equipment load (W/m^2)	11.84	10	0	11.84	1.07	11.84	16.1485	11.84	32.29	4.3
Ventilation rate ($m^3/s\ m^2$)	0.00236	0	0	0.0024	0	0.0024	0.00708	0.00236	0.00236	0
Setpoint temperature (°C heating/cooling)	18/26	18/26	18/26	0/0	18/25	18/26	18/26	18/26	18/26	0/0
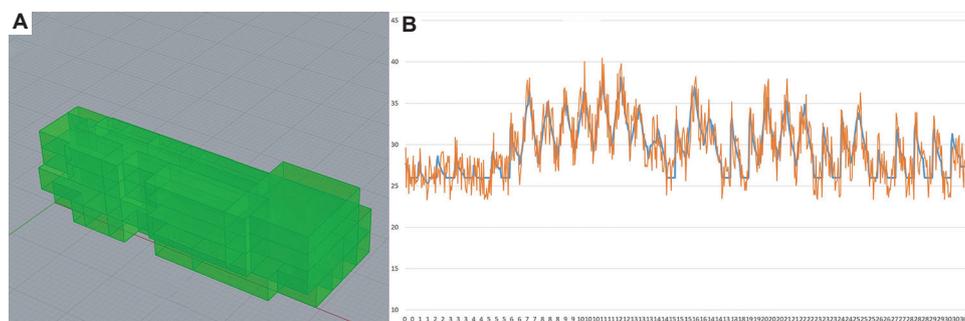
Figure 3. Screenshots of the model and its verification results. (A) Screenshot of the building model; (B) Comparison of temperature readings (orange line: Field measurement, blue line: Simulated result).

In the Wallacei optimization setup, the total number of generations was set to 32, with 32 solutions per generation. In total, over 1,000 potential solutions were generated. The crossover probability and random seed

were set to 0.9 and 1, respectively. The entire optimization process lasted over 15 h. Figure 4B shows the distribution of all generated solutions across the three objective dimensions.

Table 3. Summary of retrofit options

Retrofit options	Name	Conductivity (W/m K)	Density (kg/m³)	Specific heat (J/kg K)	Price CNY/m³
Insulation materials for the floor, exterior wall, and roof	EPS	0.037	18	1,300	600
	XPS	0.032	22	1,450	800
	PU	0.024	35	1,400	1,200
	Rock wool	0.04	140	840	500
	Glass wool	0.036	32	840	400
	Foam glass	0.058	140	800	1,000
	Perlite	0.085	400	800	300
Insulation thickness (m)	0.00/0.05/0.1.0/0.15/0.20/0.25				
	Name	**U-value (W/m² K)**	**SHGC**	**Transmittance**	**Cost (CNY/m²)**
Glazing options	Original metal frame 6 mm	5.15	0.85	0.9	60
	Low-e 6 mm	3.72	0.63	0.73	200
	6G+12A+6G	2.59	0.75	0.81	150
	6Low-e+12A+6G	1.63	0.46	0.68	300
	6Low-e+12Ar+6G	1.44	0.45	0.623	350
	6G+12A+6G+12A+6G	1.71	0.67	0.74	300
	6Low-e+12A+6G+12A+6G	1.23	0.42	0.62	500
	6Low-e+12Ar+6G+12A+6G	1.01	0.42	0.62	550
Shading depth (m)	0.00/0.15/0.30/0.45/0.60				

Abbreviations: A: Air; Ar: Argon; CNY: Chinese Yuan; EPS: Expanded polystyrene; G: Glazing; Low-e: Low-emissivity; PU: Polyurethane; SHGC: Solar heat gain coefficient; XPS: Extruded polystyrene.
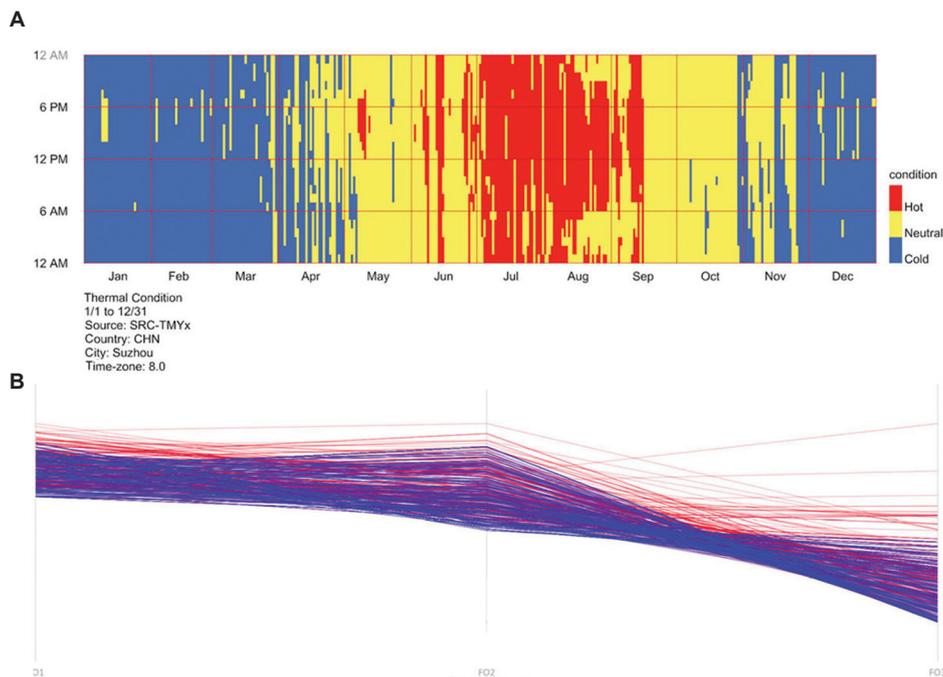

Figure 4. Simulation results. (A) The universal thermal climate index indicator throughout the year. (B) The parallel coordinate plot showing the distribution of generated solutions.

4.4. Result of the optimization

The optimization process yielded about 1,000 renovation scenarios that balance environmental comfort, initial cost, and energy efficiency. These strategies include specific recommendations on insulation improvements, window upgrades, shade design, and air seal strips. The results demonstrate significant potential improvements in both comfort levels for residents and the overall energy performance of the building. As shown in Figure 5, the potential retrofit option includes 10 genes.

In this study, the Wallacei component generated 114 solutions to form the Pareto front, as shown in Figure 6A. The solutions on the Pareto front are represented by purple cubes enclosed with yellow envelopes. The solution with the best performance in terms of cooling and heating loads is Generation 24, Solution 4, with 337,412 kWh, with a thermal comfort value of approximately 1.92, and a total cost of about 817,133 CNY. The individual in Generation 26, Solution 4 ranked first in thermal comfort, with a fitness value of 1.82. The lowest-cost option is Generation 5, Solution 5, with a cost of about 120,000 CNY, cooling and heating loads of approximately 422,194 kWh, and a thermal comfort value of about 2.28.

The most balanced option is Generation 16, Solution 23, ranking 126th, 469th, and 397th in the three objectives among all generated solutions. This individual represents the most balanced state achievable. The cooling and heating loads are about 359,410 kWh, with a thermal comfort value of approximately 2.01 and a total cost of 381,377 CNY. Based on the simulation results, no extra insulation material is required for the floor. The suggested insulation material for the exterior wall is 0.1 m thick rock wool, and for the roof, 0.2 m thick glass wool. The recommended louver depth is about 0.45 m. The suggested glazing type is 6Low-e+12Ar+6G. The recommended aperture ratio is about 0.3 for the north side and 0.4 for the south side.

Figure 6B illustrates the Pareto front solutions generated through the NSGA-II optimization, which were subsequently categorized into three clusters using the K-means clustering algorithm. This classification helps clarify distinct retrofit strategy tendencies based on the objectives of initial cost, energy consumption, and thermal comfort.

Based on feedback from healthcare center staff, the predominant barrier to building retrofitting is the high initial cost. To address this concern, the cluster analysis provides three representative solution sets that allow decision-makers to balance cost and performance according to their specific needs:
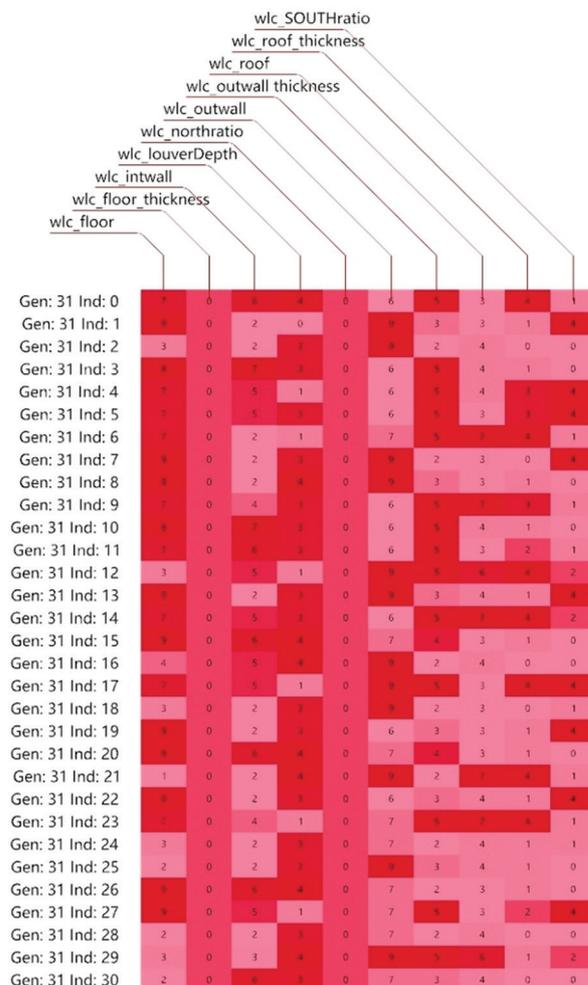

Figure 5. Gene graph of the last generation
Abbreviations: Gen: Generation; Ind: Individual; wlc: Wallacei.

(i) Cluster 2 (generation 20, solution 28):
This cluster offers solutions characterized by low initial cost, relatively higher energy consumption, and lower thermal comfort. Such strategies are particularly suitable when budget constraints are paramount. For instance, recommended retrofit measures include using glass wool insulation – 0.05 m thick for the roof and 0.1 m thick for exterior walls – as well as low-emissivity (low-e) single glazing. In addition, an aperture ratio of 0.3 for both north and south facades, with a louver depth of 0.45 m, is suggested. These cost-effective options provide a viable pathway for facilities with limited financing.

(ii) Cluster 3 (generation 9, solution 21):
In contrast, this cluster identifies solutions with higher initial costs but offers improved thermal comfort and reduced heating and cooling loads. These strategies are best suited for scenarios where budget constraints

are less critical, allowing for investments that yield long-term energy savings and enhanced occupant well-being.

(iii) Cluster 1 (generation 16, solution 23):
    This cluster represents a balanced approach, offering neutral performance across all three objectives. The solutions in this group can serve as a middle-ground option for decision-makers who wish to balance initial costs, energy performance, and thermal comfort without prioritizing one aspect disproportionately.

Table 4 provides a comprehensive summary of the potential retrofit strategies, categorizing them under various criteria – such as best scenarios in cooling and heating, optimal thermal comfort, and minimum initial cost – as well as by cluster grouping. This detailed overview is intended to assist facility managers and policymakers

in selecting a retrofit strategy that aligns with their financial resources and performance goals. It is observed that cooling and heating energy consumption peaks at 452,356 kWh and bottoms out at 337,412 kWh, with costs ranging between 119,184 CNY and 817,133 CNY.

To further enhance practical application, decision-makers are encouraged to adopt a structured decision framework that integrates both quantitative performance metrics and qualitative considerations. One effective approach is to use a multi-criteria decision analysis tool, which can systematically rank retrofit options based on weighted criteria such as initial cost, energy performance, thermal comfort, and occupant well-being. For example, decision-makers might assign higher weights to initial costs in cases where funding is severely limited, thereby prioritizing options from Cluster 2. Conversely, if long-
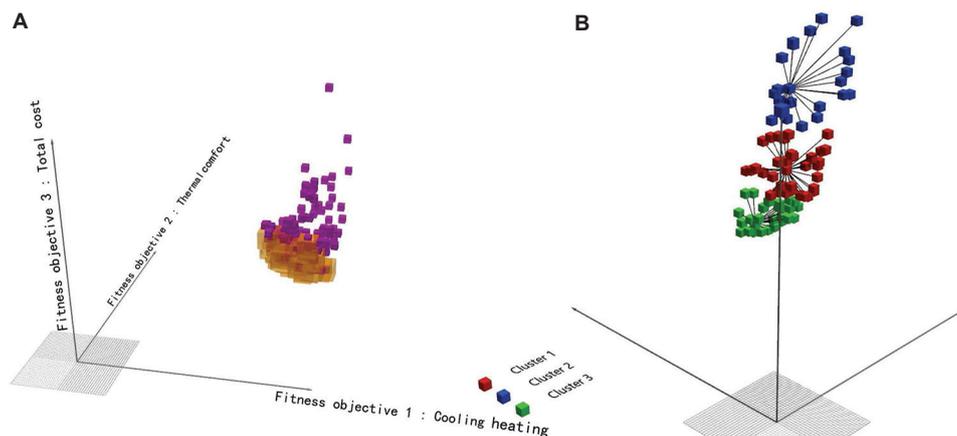

Figure 6. Distribution of simulated solutions. (A) The Pareto front; (B) the K-means cluster algorithm on the solutions.

Table 4. Summary of retrofit measures across various scenarios

Retrofit measures	Best scenarios in cooling and heating	Best scenarios in thermal comfort	Best scenarios in initial cost	Cluster 1	Cluster 2	Cluster 3
Wall thickness (m)	0.25	0.25	0.1	0.2	0.15	0.05
Wall material	Rock wool	Rock wool	Perlite	Glass wool	Glass wool	Glass wool
Roof thickness (m)	0.2	0.2	0	0.15	0.1	0.05
Roof material	PU	PU	PU	SEPS	Rock wool	Glass wool
Glazing	6low-e+12Ar+6G+12A+6G	6G+12A+6G+12A+6G	6G+12A+6G	6Low-e+12A+6G+12A+6G	6Low-e+12Ar+6G	6G+12A+6G
North window ratio	0.3	0.3	0.3	0.3	0.3	0.3
South window ratio	0.3	0.7	0.3	0.4	0.4	0.3
Louver	0.45	0.15	0.15	0.45	0.15	0.45
Cooling and heating (kWh)	337,412	452,356	422,194	359,410	398,146	352,926
PMV	1.92	1.82	2.28	2.01	2.22	1.95
Cost (CNY)	817,133.6	796,408.6	119,184.2	381,377.6	167,510.9	569,505.9

Abbreviations: A: Air; Ar: Argon; CNY: Chinese Yuan; EPS: Expanded polystyrene; G: Glazing; low-e: Low-emissivity; PU: Polyurethane.

term energy savings and enhanced comfort are paramount, options from Cluster 3 would receive a higher ranking. A case example within our study illustrates this process: a facility manager with moderate budget constraints used a multi-criteria framework to evaluate retrofit scenarios, ultimately selecting a balanced option from Cluster 1 that provided a reasonable compromise between cost and performance. This framework allows stakeholders to tailor their choices according to specific strategic priorities and local conditions, ensuring that the selected retrofit strategy not only meets technical performance targets but also aligns with broader organizational and societal objectives. Integrating such a decision framework bridges the gap between technical optimization and real-world implementation, offering a replicable and globally relevant methodology that can be adapted across diverse contexts and retrofit challenges.

5. Discussion

The optimized retrofit strategies reveal clear trade-offs between cost reduction and thermal comfort improvements. The analysis indicates that while solutions with lower initial costs are attractive from a budgetary perspective, they often compromise thermal comfort and energy performance. Specifically, options that prioritize cost savings tend to involve less intensive insulation measures or simpler glazing systems, which, although economically favorable, result in higher energy consumption and reduced thermal comfort. In contrast, achieving higher levels of thermal comfort generally requires more substantial investments in advanced materials and design features, leading to a significant increase in initial costs. The Pareto front illustrates this inherent conflict, showing that decision-makers must balance immediate financial outlays against long-term occupant well-being and energy efficiency. This trade-off is especially critical in eldercare settings, where the health and safety of residents are paramount. Recognizing these conflicts, policymakers and facility managers are encouraged to explore innovative financing mechanisms and incentives that can help mitigate the financial burden of high-performance retrofits while still delivering the necessary improvements in thermal comfort.

Moreover, while cost-effective solutions are emphasized, our study recognizes that financial constraints can be mitigated through innovative financing mechanisms and policy incentives. Policymakers are encouraged to consider subsidies, low-interest loans, and tax incentives that could help offset the higher upfront costs associated with more comprehensive retrofit strategies. Such mechanisms not only facilitate the implementation of advanced retrofits but also ensure long-term sustainability by improving energy performance and occupant comfort.

By visualizing the Pareto front and employing cluster analysis, this research provides a clear framework for decision-makers. It offers practical insights into how different retrofit strategies can be prioritized based on both technical performance and economic feasibility, thereby paving the way for more informed, balanced, and sustainable building retrofit decisions.

6. Conclusion

This study introduced a comprehensive framework for retrofitting eldercare buildings by integrating architectural design principles with advanced optimization algorithms. The approach aimed to enhance the living quality of elderly residents while achieving energy efficiency and sustainability. The study emphasizes the value of interdisciplinary methods in addressing the multifaceted challenges of eldercare facility retrofitting. The main findings of the study are summarized as follows:

(i) Optimal solution identification: The most balanced retrofit solution, based on the Wallacei plugin's optimization process, was identified as Generation 16, Solution 23.

(ii) Budget-conscious selection: For scenarios with budget constraints, cluster analysis proved useful. In this study, Cluster 2, Generation 20, Solution 28 emerged as a cost-effective option with relatively high energy consumption.

(iii) Material and design recommendations: Analysis of the gene graph from the most balanced solution highlights specific material and design choices:
   a. The preferred glazing type was 6Low-e+12Ar+6G.
   b. The optimal louver depth was approximately 0.45 m.
   c. No additional floor insulation is required.
   d. The suggested insulation materials for the roof and exterior walls are glass wool and rock wool, respectively.

These findings offer several avenues for informing future policy decisions regarding eldercare facility retrofits. By integrating a multi-objective optimization framework – specifically the NSGA-II algorithm combined with K-means clustering – this study presents a novel approach that not only identifies cost-effective solutions but also explicitly delineates the trade-offs between initial investment, energy consumption for cooling and heating, and thermal comfort. This study advances prior research by integrating NSGA-II with architectural design to offer a holistic framework that balances occupant well-being, energy efficiency, and cost, marking a departure from siloed approaches. Policymakers can leverage these insights to design targeted retrofit incentives and financing mechanisms that mitigate the high upfront costs of advanced retrofits while ensuring

enhanced thermal performance and occupant safety. In doing so, regulatory strategies can be better aligned with the long-term objectives of reducing energy consumption and improving occupant health outcomes.

In addition to the above, this research makes several novel contributions. The integration of the NSGA-II algorithm with the Wallacei plugin and K-means clustering created a robust decision-making tool that translates complex multi-objective trade-offs into actionable retrofit strategies. This approach not only bridges the gap between advanced computational methods and practical architectural applications but also provides a replicable decision framework that decision-makers can adopt to prioritize retrofit options based on specific contextual needs. These methodological innovations and interdisciplinary integrations set this work apart from existing approaches, offering policymakers targeted insights to design retrofit incentives and financing mechanisms that address high upfront costs while ensuring enhanced thermal performance and safety.

Looking ahead, future research will focus on applying these recommendations to the case study building and assessing their effectiveness under real-world conditions. In addition, the research framework has the potential to be adapted for other building types and geographical regions, broadening its scope and impact in sustainable retrofitting practices.

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Conflict of interest

Saffa Riffat is an Editorial Board Member of this journal but was not involved in the editorial or peer-review process for this paper, either directly or indirectly. Separately, the other authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Author contributions

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Not applicable.

Consent for publication

Not applicable.

Availability of data

Data are available from the corresponding author upon reasonable request.

References

1. Wang R, Lu Y, Zhang J, Liu P, Yao Y, Liu Y. The relationship between visual enclosure for neighbourhood street walkability and elders' mental health in China: Using street view images. *J Transp Health*. 2019;13:90-102.

   doi: 10.1016/j.jth.2019.02.009

2. Gui Z, Ji W, Wang Y, *et al.* Severer air pollution, poorer cognitive function: Findings from 176,345 elders in Northwestern China. *Ecotoxicol Environ Saf*. 2024;271:116008.

   doi: 10.1016/j.ecoenv.2024.116008

3. Feng Z, Glinskaya E, Chen H, *et al.* Long-term care system for older adults in China: Policy landscape, challenges, and future prospects. *Lancet*. 2020;396(10259):1362-1372.

   doi: 10.1016/S0140-6736(20)32136-X

4. Xue Y, Temeljotov-Salaj A, Lindkvist CM. Renovating the retrofit process: People-centered business models and co-created partnerships for low-energy buildings in Norway. *Energy Res Soc Sci*. 2022;85:102406.

   doi: 10.1016/j.erss.2021.102406

5. Ahrentzen S, Erickson J, Fonseca E. Thermal and health outcomes of energy efficiency retrofits of homes of older adults. *Indoor Air*. 2016;26(4):582-593.

   doi: 10.1111/ina.12239

6. Institute of Medicine (US) Committee on the Future Health Care Workforce for Older Americans. *Retooling for an Aging America: Building the Health Care Workforce*. Washington, DC: National Academies Press; 2008.

7. Peters T, Verderber S. Biophilic design strategies in long-term residential care environments for persons with dementia. *J Aging Environ*. 2022;36(3):227-255.

   doi: 10.1080/26892618.2021.1918815

8. Kumar S, Sakagami K, Lee HP. From Sustainability to Regeneration: Improving Indoor Environment Quality Through Innovative Design [Preprint]; 2025.

9. Li Y, Du H, Kumaraswamy SB. Case-based reasoning approach for decision-making in building retrofit: A review. *Build Environ*. 2024;248:111030.

    doi: 10.1016/j.buildenv.2023.111030

10. Ge J, Lu J, Wu J, Luo X, Shen F. Suitable and energy-saving retrofit technology research in traditional wooden houses in Jiangnan, South China. *J Build Eng*. 2022;45:103550.

    doi: 10.1016/j.jobe.2021.103550

11. Kazerouni F, Azarbad K, Delgarm N. Multi-objective optimization of building energy efficiency via NSGA-II: A simulation-based approach. Norway: International Conference on Engineering and Technology; 2019.

12. Zhang L, Qi Z, Yang X, Jiang L. Intelligent optimization pathway and impact mechanism of age-friendly neighborhood spatial environment driven by NSGA-II and XGBoost. *Appl Sci*. 2025;15(3):1449.

    doi: 10.3390/app15031449

13. Chen Z, Cui Y, Zheng H, Ning Q. Optimization and prediction of energy consumption, light and thermal comfort in teaching building atriums using NSGA-II and machine learning. *J Build Eng*. 2024;86:108687.

    doi: 10.1016/j.jobe.2024.108687

14. Oyekale J, Petrollese M, Cau G. Multi-objective thermo-economic optimization of biomass retrofit for an existing solar organic Rankine cycle power plant based on NSGA-II. *Energy Reports*. 2020;6:136-145.

    doi: 10.1016/j.egyr.2019.10.032

15. Makkar P, Sikka S, Malhotra A. Empirical evaluation of NSGA II, NSGA III, and MOEA/D optimization algorithms on multi-objective target. In: *Soft Computing: Theories and Applications: Proceedings of SoCTA 2020*. Vol. 1. Germany: Springer; 2022. p. 23-31.

16. Mendes A, Bonassi S, Aguiar L, *et al*. Indoor air quality and thermal comfort in elderly care centers. *Urban Clim*. 2015;14:486-501.

    doi: 10.1016/j.uclim.2014.07.005

17. Ji Y, Feng X, Zhao H, Xu X. Study on the Thermal Comfort, Use and Microclimate Preferences of the Elderly in Residential Communities [SSRN Preprint].

18. Roelofsen P, Jansen K, Vink P. A larger statistical basis and a wider application area of the PMV equation in the Fanger model: Application area of the PMV equation. *Intell Build Int*. 2022;14(4):1-8.

    doi: 10.1080/17508975.2021.1928595