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Multi-objective optimization on sustainable retrofit of historical buildings using NSGA-II Algorithm: A case study of Suzhou

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Abstract

The aim of the study is to advance the revitalization of historical buildings, it is crucial to preserve their historical character while addressing challenges such as poor thermal performance and low environmental comfort, making them better suited to modern needs. Focusing on historical buildings in Suzhou, this study examines integrated renovation strategies that balance objectives such as historical preservation, energy efficiency, cost reduction, and improved environmental comfort. The theoretical component of the research seeks to evaluate the potential for sustainable retrofitting of historical buildings in Suzhou. It aims to reveal the underlying relationships between historical preservation, sustainability goals, and retrofit strategies, ultimately proposing a set of approaches that address multiple objectives. This framework is intended to support more holistic decision-making for green renovations of historical buildings. By offering comprehensive solutions, the research aspires to advance environmental sustainability while maximizing the value of urban historical and cultural heritage preservation.

Keywords: Heritage building; Sustainable retrofit; Multi-objective optimization

1. Introduction

Suzhou, often referred to as the "Venice of the East," is renowned for its classical gardens, canals, and traditional Chinese architecture. The city has a history that dates back over 2,500 years, making it one of the oldest cities in China. Historically, Suzhou was a major center for silk production and trade, contributing to its economic prosperity and the development of a unique architectural style. These buildings are not only valuable cultural assets but also serve as a testament to the city's architectural legacy. Traditional buildings in Suzhou reflect the Jiangnan style, characterized by whitewashed walls, black-tiled roofs, and intricate wooden carvings. This style emphasizes simplicity, elegance, and a deep connection with nature.

However, many of these historical structures suffer from poor thermal performance and low environmental comfort, making them less suitable for modern occupancy and

use. Addressing these issues is essential for the sustainable revitalization of these buildings, ensuring they remain functional and valuable parts of the urban fabric. Apart from the modern building retrofit, the primary challenge in retrofitting historical buildings lies in balancing the need for modernization with the imperative of preserving their distinguishing features. Conventional buildings often have outdated construction methods and materials, leading to inefficiencies in energy use and comfort levels.[1,2] Strict protection regulations limit the scope and nature of modifications to these buildings, making this issue even more complicated. Therefore, finding retrofit strategies that can improve energy efficiency, reduce operational costs, and enhance environmental comfort, all while maintaining the historical character of these buildings, is a complex and trade-off needed task.

The main aim of this study is to find the suitable retrofit strategies, focusing not only on the common retrofit objective, such as energy consumption and initial cost reduction, and thermal comfort improvement but also the historical preservation. On the basis of maintaining the architectural significance of the building, identifying the retrofit strategies to improve energy efficiency and thermal comfort of the heritage buildings in Suzhou is necessary. Hence, this study is divided into two parts. The first part is to evaluate the suitability of the retrofit strategies on the heritage building and extract the compatible strategies, while the second part is to analyze the various retrofit scenarios comprised by the above strategies with multi-criteria decision analysis method to identify the most trade-off scenarios. The findings and recommendations of this study can support the broader efforts of urban revitalization, making historical districts more vibrant and livable, responding to the call for preservation and active utilization on heritage buildings from President Xi.[3,4]

2. Methodology

In this study, retrofit strategies identified from previously published research will be assessed for their suitability in the context of historical buildings, aiming to determine potential options that define the research scope. Subsequently, a parametric model of a sample building will be developed using Rhinoceros, which has been widely used in existing literature.[5] The accuracy of simulation will be verified through a comparison of simulation results with actual measured data. The final phase of the study focuses on identifying retrofit scenarios that simultaneously achieve energy consumption reduction, cost savings, and improved thermal comfort within the defined research scope. To accomplish this, Wallacei and Ladybug Tools components are employed to prioritize strategies, enabling

an optimized approach to sustainable retrofitting for historical buildings.[5]

3. Literature review

Historic buildings embody cultural heritage and architectural craftsmanship that contribute significantly to a local identity and history. In recent years, academic discourse and policy discussions have increasingly emphasized the need to protect heritage buildings while adapting them to contemporary functional demands. This literature review synthesizes existing research on the protection of historic buildings, discussing the necessity for preservation, the regulatory frameworks in place, strategies for integrating modern requirements, and the constraints and opportunities associated with sustainable retrofits.

3.1. Overview of historical preservation principles

Preserving historic buildings is crucial for several reasons. They are important for strengthening cultural and social identity, promoting local traditions, and strengthening community ties. Moreover, these buildings can contribute to economic growth by attracting tourists and investments, especially through adaptive reuse. In addition, reusing these buildings is more environmentally sustainable compared to demolition and new construction, aligning with broader sustainable development objectives.[6,7] In consideration of the great amount of existing historic buildings in China, it is necessary to preserve the historic building and renovation for modern requirements.

Nowadays, regulatory frameworks play a critical role in the protection and adaptive reuse of historic buildings. National and local codes, as well as international charters, have been established to guide conservation efforts. These frameworks often include a range of measures aimed at balancing historical preservation with practical, modern uses.[7,8] For instance, legal protections and zoning regulations can restrict alterations that might compromise the historical integrity of a building, while still allowing for sympathetic adaptations that enhance its functionality and appeal.[5] Moreover, modern building codes have increasingly incorporated provisions to ensure that historic buildings can be retrofitted to meet contemporary safety and energy efficiency standards. This often requires innovative solutions that reconcile the need to preserve historical features with the need to ensure that the building is safe and suitable for modern use.

Integrating historic buildings into modern society requires careful consideration of their functionality without compromising their heritage value. Technological innovations play a crucial role in integrating modern

functionality into historic buildings. Advances in construction technology, such as energy-efficient retrofitting methods and smart management systems, offer new possibilities for updating these buildings without losing their historical significance.[9,10] These innovations help to bridge the gap between preservation and the need for contemporary amenities. A recurring theme in the literature is the tension between preserving original features and updating historic buildings to meet present-day standards. Researchers emphasize the importance of multidisciplinary collaboration among architects, engineers, historians, and policymakers to develop solutions that respect the past while accommodating future needs. This collaboration ensures that historic buildings can continue to play a meaningful role in modern society while maintaining their cultural and historical value.

3.2. The retrofit on the historical buildings

The sustainable retrofitting of historic buildings presents a unique combination of challenges and opportunities that have been thoroughly examined in the literature. Regulatory and financial barriers also present significant challenges. While regulatory frameworks aim to protect historic buildings, they can sometimes limit the extent of permissible modifications, thereby creating constraints. In addition, the higher costs associated with bespoke retrofit solutions can deter potential investors.[11,12] Despite these challenges, sustainable retrofitting offers numerous opportunities. Innovations in energy conservation, such as the use of low-impact materials and renewable energy integrations, can enhance the environmental performance of historic buildings while preserving their character. Pilot projects and collaborative research have shown that combining traditional construction methods with modern technology can lead to resilient and energy-efficient retrofits.[2,5,13]

The retrofit of historical buildings requires thorough research and engineering plans to achieve the goals of not altering their authenticity and integrity. It is necessary to use the principle of minimum disturbance as a guideline and use appropriate technologies to achieve the goal of reusing historic buildings.[3] However, in practical engineering, the complexity of engineering decisions and the weak performance of historical buildings have become the biggest obstacles to their reuse.[14] Therefore, it is necessary to scientifically and rationally analyze the transformation of historical buildings and help them to burst out new vitality while inheriting the special cultural value of heritage buildings.

In the context of urban renewal and the carbon peaking and carbon neutrality goals in China, the retrofit of existing buildings has increasingly become a hot topic in academic research. Due to the diverse needs of the user population, the objectives of the renovation and optimization of existing buildings have also evolved from façade renewal, functional transformation to deep objectives such as environmental comfort, energy conservation,[3] carbon emissions,[15] and cost optimization.[15,16] As for the retrofit of heritage building, the preservation of architectural integrity is also of vital importance during decision-making process.

In the sustainable historical building behavior guidance proposed by the UK government, the energy-saving efficiency, environmental comfort, and historical value protection of renovation strategies are taken as the behavioral guidelines for building heritage protection. Ge[5] taking the old house of the Luo family in Hangzhou as an example, a comprehensive evaluation system was established based on the three sub-objectives of adaptability, economy, and energy efficiency of retrofit strategies, and the non-dominated genetic algorithm (NSGA-II) was used to find suitable renovation strategies. In summary, the optimization goals generally include the protection of historical value, cost, energy-saving effect, carbon emissions, environmental comfort, and so on.

3.3. Reviews on sustainable retrofits

The suitability of renovation strategies for heritage buildings is influenced by several factors, such as their historical value, architectural style, structural condition, and the specific goals of the renovation (*e.g.*, enhancing thermal comfort, reducing energy usage, or preserving cultural heritage).

Most previously published studies have primarily concentrated on passive design strategies or improvements to the building envelope.[1,5,13,17-21] These measures include adding insulation, upgrading windows, and minimizing air leakage, all of which effectively enhance thermal comfort and reduce energy consumption. Among these, glazing replacement has emerged as the second most frequently discussed strategy due to its notable energy efficiency and cost-effectiveness.[1,5,17-19,21] In addition, some studies have proposed complementary strategies, such as upgrading heating, ventilation, and air conditioning (HVAC) systems,[19,21] incorporating renewable energy sources,[22,23] and adopting LED lighting.[19,21] These findings provide valuable insights into the prioritization of retrofitting strategies based on practical experience.

However, the selection of appropriate strategies is highly dependent on the specific conditions of each heritage building. Therefore, a more comprehensive evaluation is necessary. This should consider not only historical and architectural factors but also include detailed energy audits and economic analyses, as discussed further below.

3.4. Challenges in retrofitting heritage buildings

Heritage buildings are often protected by local, national, or international regulations that enforce strict guidelines on modifications, which aim to preserve their historical and architectural integrity. These regulations frequently limit the scope of retrofit interventions, which are often focused on structural repairs. Typically, any retrofit project for a heritage building must be approved by multiple administrative bodies, making the process time-consuming, complex, and challenging for non-specialists. Furthermore, regulations for heritage buildings often mandate that their exterior appearance remains unchanged, restricting the use of modern materials and technologies that might be visible from the outside. As a result, traditional materials and construction techniques are often required, which can be more costly and less efficient than modern alternatives. This limits the feasibility of sustainable retrofitting, leaving many occupants of heritage buildings faced with high energy consumption and poor thermal comfort but few options for improvement.

4. Description of the sample building

An investigation of over one hundred historic buildings in Gusu District, Suzhou, revealed that structures with three standard widths are the most common, comprising 67% of the surveyed buildings. Similarly, buildings with three standard depths also account for a significant proportion. Based on these findings, a representative sample building was chosen to reflect the thermal performance of traditional residential buildings in the area. The selected sample building, located at No. 29, Shuitan Street, Gusu District, Suzhou, has a total area of approximately 167 m² across two floors, as shown in Figure 1. It is a well-preserved wooden/brick structure situated within a traditional lane and serves as a typical example of local heritage architecture. At present, the sample building houses three permanent residents, including two elderly individuals and one rental tenant. This demographic profile further highlights the

need for cost-effective and accessible retrofit solutions tailored to the building's context.

During the investigation, questionnaire-based survey was conducted to gauge occupants' willingness to retrofit their buildings. Results indicated that the primary barriers to retrofitting were high initial costs and a lack of professional knowledge. Occupants and landlords typically operate under constrained budgets and place less emphasis on preserving the historical value of their buildings. As a result, retrofit recommendations must align with varying budget levels to ensure practical implementation.

Detailed architectural plans and data from sample buildings were collected to create an accurate parametric simulation, which serves as the basis for simulation and analysis. A series of detailed measurements were also conducted. These measurements encompass various aspects of thermal comfort and energy consumption, providing critical data for subsequent simulations and optimization.

The following parameters were measured:
1. Thermal property of the building envelops
   - Measurement tools: K-type thermocouples, Centertek 309 thermometer, and Hukesflux heat flux sensors were implemented to capture the thermal transmittance of building envelopes.
   - Data collected: Heat flux sensors and thermocouple readings were taken to calculate the U-value of building envelopes.

2. Energy consumption
   - Measurement tools: The records of energy meters were collected to monitor heating/cooling energy consumption.
   - Data collected: Data on energy consumption patterns were collected over summer to capture variations in usage and identify opportunities for energy efficiency improvements.

The summary of the measured thermal property of sample building is listed in Table 1.
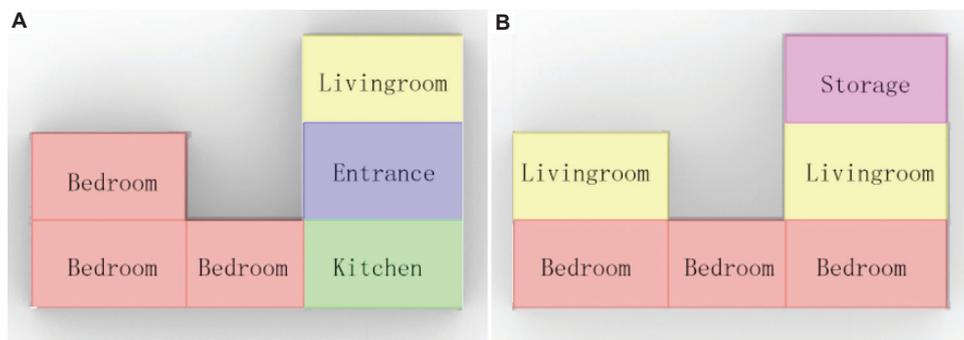

Figure 1. The plan of the sample building: (A) ground floor, and (B) first floor

5. Retrofit strategies

5.1. Suitability of retrofitting strategies in the context of historical building

As illustrated in Figure 2, our study adopted a hybrid approach that integrated analytic hierarchy process (AHP) with a fuzzy comprehensive evaluation to rigorously assess retrofit strategies for historic buildings. A hierarchical structure of evaluation criteria has been developed. The experts performed pairwise comparisons of the criteria, resulting in a detailed pairwise comparison matrix (Table 2 for the full calculation data). To establish the evaluation criteria, we engaged a panel of 10 experts from diverse fields including historic preservation, sustainable engineering, and civil engineering. These experts were selected for their extensive experience in historic preservation and sustainable retrofitting. Their input was gathered through structured interviews and questionnaires to refine the criteria originally derived from prior studies.[24] This collaborative process ensured that the evaluation framework was both comprehensive and reflective of the

real-world challenges in historic building conservation. The consistency ratio of 0.011 confirmed the acceptability of the judgment matrix. Impact weights for four indexes on historic preservation (Table 3) ranged from 0.095 to 0.397, with appearance and structural security having the highest weights, highlighting the importance of retrofit strategies like ventilation from a preservation perspective.

In Table 3, the proposed retrofitting strategies prioritize key aspects to ensure compatibility with heritage buildings. In terms of appearance, the components are carefully selected to seamlessly blend with the building's aesthetics, minimizing any visual disruption and preserving its architectural integrity. Structural security is a critical consideration, with solutions designed to ensure compatibility with the existing structure while maintaining the building's safety and stability. However, installation difficulty is acknowledged as a potential challenge, particularly for labor-intensive or invasive solutions involving hard-to-access components, which could impact the building's structure during the retrofitting process. To address this, the research emphasizes reversibility, selecting components that are easy to install and can be removed without significant damage, enabling the building to be restored to its original state if required. These considerations collectively aim to enhance the building's functionality while preserving its historical and cultural value.

Following the AHP phase, a fuzzy comprehensive evaluation was conducted to translate qualitative judgments into quantitative measures. In this step, each evaluation index was scored on a scale from 0 to 10, where a lower score (Grade 1) indicated a highly invasive impact on the historic value, and a higher score (Grade 9) indicated minimal impact. The fuzzy evaluation employed triangular membership functions to define linguistic variables representing different impact levels. This approach allowed us to objectively combine the weighted qualitative assessments, ensuring a transparent and replicable evaluation process.

The analysis identified LED replacement and airtightness improvements as the most adaptable strategies for preserving historic value. Glazing upgrades, smart controls, and high-performance HVAC systems also showed

Table 1. Summary of thermal property of sample building

Component	Structure	Indicators
Exterior wall	Plastering 10 mm+Cement mortar 15 mm+280 Brick wall+Cement mortar 15 mm	1.49 W/(m²·K)
Interior Wall	Mortar 10 mm+Brick 190 mm+mortar 10 mm	1.44 W/(m²·K)
Window	Wooden frame with single glazing in 6 mm	4.4 W/(m²·K)
Roof	Gray tile 10 mm+Waterproofing membrane 2 mm+Fir board 12 mm	3.64 W/(m²·K)
Floor	Square brick (50 mm) + Cement mortar (30 mm) + Concrete (100 mm) + Soil	2.54 W/m²·K
Infiltration	Poor	0.0006 m3/s per m² façade
Door	Wooden door in 25 mm	2.98 W/(m²·K)
HVAC	Split air conditioner	$T_{cooling}$=26, $T_{heating}$=18
Shades	No	

Abbreviation: HVAC: Heating, ventilation, and air conditioning.
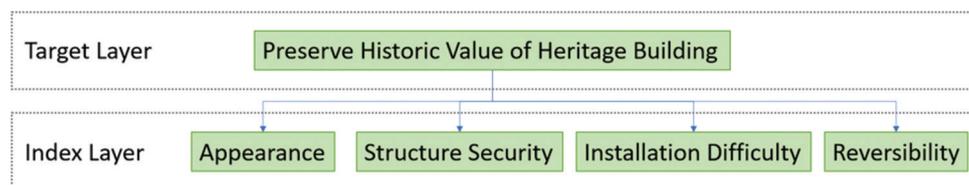

Figure 2. The hierarchy structure with main evaluation criteria

Table 2. The summary of the potential retrofit strategies

Potential Solutions	Name	Conductivity	Density	Specific heat	Price CNY/m³
Inner insulation material for floor, exterior wall, and roof	EPS	0.037	18	1,300	600
	SEPS	0.033	18	1,300	700
	XPS	0.032	22	1,450	800
	SXPS	0.024	30	1,450	900
	PU	0.024	35	1,400	1200
	MPF	0.024	35	1,450	2500
	Rock wool	0.04	140	840	500
	Glass wool	0.036	32	840	400
	Foam glass	0.058	140	800	1000
	Perlite	0.085	400	800	300
Insulation thickness (m)					
0	0.05	0.1	0.15	0.2	0.25
	Name	**U-value**	**SHGC**	**transmittance**	**Cost CNY/m²**
Glazing	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
Air seal strips (m³/s per m² façade)					
0.0006	0.0003	0.0001			

Abbreviations: EPS: Expanded polystyrene; MPF: Modified phenolic foam; PU: Polyurethane; SEPS: Styrene ethylene propylene styrene; SXPS: Strengthened extruded polystyrene; XPS: Extruded polystyrene.

Table 3. Impact weights of various indicators

Index	Appearance	Structure security	Installation difficulty	Reversibility
Impact weight	0.397	0.346	0.162	0.095

strong applicability, while inner insulation preserved the appearance of heritage buildings. Conversely, other strategies showed limited suitability. These strategies offer a balanced approach to improving building performance while maintaining historic and architectural integrity.

5.2. The potential retrofit options

The potential retrofit options in this study cover insulation material for envelopes, the thickness of insulation, air seal strips, glazing type, and the depth of the shades. Table 2 summarizes the retrofit options in this study. The insulation materials cover organic and inorganic materials. To minimize the intervention on the historic values, the thickness of the insulation material is limited to <0.25 m.

This limit was determined after considering several factors. The research done by Walker et al.[25] evaluates the cost-effectiveness of the insulation in 0.20 m. This research would like to cover all potential retrofit options, with the maximum thickness set as 0.25 m. There are also over eight types of potential glazing types. Moreover, the air change rate with various percentages of application on the air seal strips account ranges from 0.0001 to 0.0006 m³/s per m² façade.

6. Case study analysis

6.1. Simulation setup

A comprehensive parametric model of the sample building was developed using Rhino, a leading Computer Aided Design (CAD) tool known for handling complex geometries. This model was seamlessly integrated into Grasshopper, a visual programming environment that allows for dynamic, parametric control over design iterations. This combination is especially advantageous in

the context of retrofitting historic buildings, as it supports iterative exploration of design scenarios while adhering to preservation constraints. Within the Grasshopper environment, Ladybug Tools were employed to conduct detailed environmental simulations, as shown in Figure 3A. These tools provide an extensive suite for simulating solar radiation, daylighting, thermal performance, and other critical climatic factors. The building operation schedules was set by the building programme in Ladybug, as shown in Figure 3B. This functionality is crucial for evaluating how different retrofit strategies will interact with the unique environmental context, ensuring that

interventions support both energy efficiency and heritage conservation. As shown in Figure 3D, sliders were utilized in Grasshopper to select possible renovation options for a historic building. Additionally, Wallacei, shown in Figure 3E, was used to perform multi-objective optimization, balancing conflicting design goals such as thermal comfort, initial cost, and energy for cooling and heating.

The focus on initial cost over a full life-cycle cost analysis in this study was deliberate. During the field measurements, the respondents always focus on the initial cost of the retrofit. The initial cost has the biggest impacts
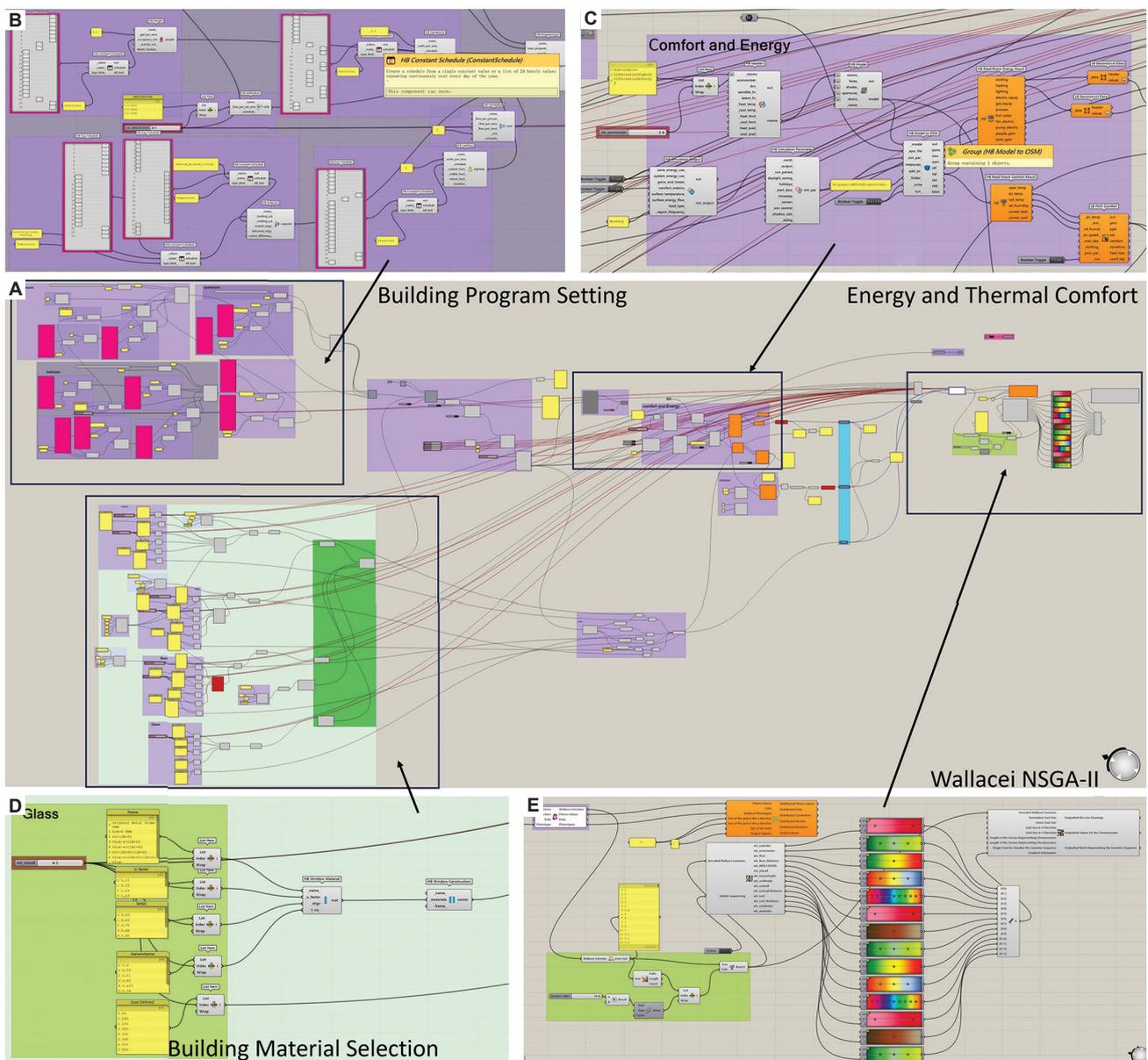

Figure 3. The screenshot of the Grasshopper. (A) The overview of the screenshot; (B) building program setting; (C) energy and thermal comfort simulation with Ladybug Tools; (D) building material selection; (E) Wallacei component.

on intentions of retrofitting. Immediate decision-making is often necessary for retrofit projects, particularly for historic buildings, where stakeholders of the building prioritize the upfront capital required due to limited budgets and the urgency of securing funding. In addition, evaluating the initial cost provides a clear baseline for assessing the feasibility of retrofit strategies, offering an instant overview of financial demands that are essential for projects adhering to strict conservation and regulatory requirements. While life cycle cost analysis is important for a comprehensive evaluation, it involves numerous uncertain assumptions about future maintenance, operational costs, and potential savings, especially in the context of historic building retrofits.

The simulation setup was meticulously designed to incorporate a wide range of parameters beyond thermal properties, including occupant loads, lighting conditions, ventilation strategies, and HVAC system setpoints. The building was segmented into five functional spaces, each set according to specific simulation modules provided by Ladybug Tools. Input parameters for these modules were derived from field questionnaires and aligned with relevant Chinese building codes, ensuring both empirical rigor and regulatory compliance. The HVAC system was set as an ideal air system, excluding consideration of the coefficient of performance of system, as shown in Figure 3C. The energy consumption in this study was defined as the sum of the heating and cooling loads. The potential benefits of air seal strips were also examined to enhance airtightness, reduce energy losses, and improve overall thermal performance.

The optimization objectives include thermal comfort, energy consumption, and initial cost in CNY. The predicted mean vote (PMV)-predicted percentage of dissatisfied model is selected as the thermal comfort index. Normally, the PMV model is to evaluate the thermal comfort of a conditioned space during whole year. However, during the transition season, spring and autumn, the thermal comfort of exterior environment is acceptable for most people. The average universal thermal climate index (UTCI) indicator in Suzhou during summer and winter is about 0.587409 and −0.963889, respectively. Thus, this study would like to specially optimize the thermal comfort during summer and winter. In Grasshopper, the Ladybug tools can be implemented to evaluate the PMV of interior room. In PMV model, the indicator ranges from −3 to +3, indicating the cold, neutral, and hot feelings. In Wallacei component, the objective of thermal comfort has been setup to minimize the sum of absolute number of PMV indicator during summer and winter. The less of the sum, the thermal comforts during summer and winter are more acceptable.

It is worth to mention that the energy consumption in this study only covers the energy consumed by HVAC system. In the Wallacei component, the total number of generations is 40 and there are 35 solutions per generation. Overall, 1,400 potential solutions have been generated. The crossover probability and random seed are set as 0.9 and 1, respectively.

6.2. Baseline simulation

In this section, the heating/cooling loads and thermal comfort have been simulated. The heating/cooling loads are 12,474 kWh in total and 86.7 kWh/m^2 in average. As shown in Figure 4, the average PMV indicator for all rooms during summer and winter is 1.74 and −2.74, respectively. It can be seen that the PMVs of rooms facing north are worse than the room facing south, especially during winter. As Suzhou is located in the region of hot summer and cold winter, the demand for heat preservation is even more urgent. The analyzed UTCI index for Suzhou during summer and winter is about 0.587409 and −0.963889, respectively. Thus, this study would like to specially optimize the thermal comfort during summer and winter.

6.3. Performance evaluation

The genetic algorithm, particularly NSGA-II, and Wallacei in Grasshopper, offers robust tools for solving optimization problems. NSGA-II, as an advanced multi-objective genetic algorithm, improves upon earlier versions by reducing complexity and enhancing performance, making it suitable for solving complex optimization problems and providing diverse and comprehensive solution sets. Wallacei, a design optimization tool based on genetic algorithms and multi-objective optimization principles, integrates seamlessly with Grasshopper, allowing designers to explore design spaces, perform parameter optimization, and search for optimal solutions efficiently. In this study, the optimization objectives include energy consumption, thermal comfort, and total initial cost.

The optimization process yielded about 1,400 renovation strategies that balance environmental comfort, initial cost, and energy efficiency. These strategies include specific recommendations on insulation improvements, window upgrades, and air seal stripes. The results demonstrate significant potential improvements in both comfort levels for residents and overall energy performance of the building. The potential retrofit option includes 14 genes in the NSGA-II algorithm, with 99 potential gene options.

The Pareto front consists of 74 solutions, the points enclosed with orange cubes in Figure 5A, with the most balanced option identified as Generation 30, Solution 4,
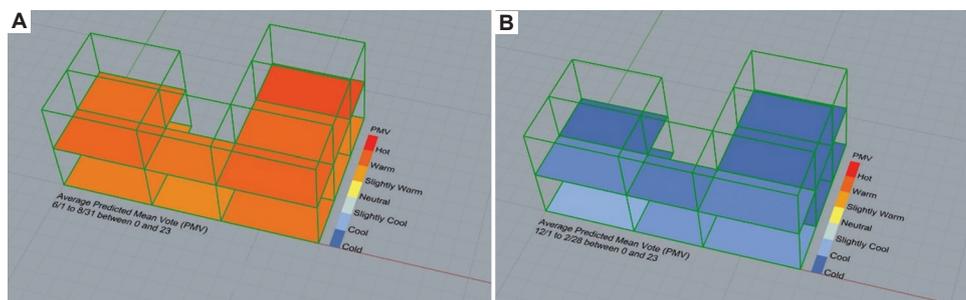
Figure 4. The PMV during summer (A) and winter (B)
Abbreviation: PMV: Predicted mean vote.

Table 4. Recommended retrofit features in Generation 30, Solution 4

Components	Measures
Exterior wall insulation	Polyurethane (PU) with a thickness of 0.05 m
Roof insulation	PU with a thickness of 0.3 m
Windows	6 mm single glazing
Airtightness	Use of air seal strips
Louvre depth	Recommended depth is 0.1 m

as shown in Table 4. This solution ranks 362nd, 3rd, and 845th across the three objectives among all generated results, representing an optimal trade-off between the criteria. In this configuration, the cooling and heating loads are approximately 6,574 kWh, with a total cost of 46,401 CNY. The thermal comfort indicators for winter and summer are improved to −1.71 and 1.25, respectively.

6.4. Cluster on result

Dividing the Pareto solutions into distinct clusters is essential to capture the diverse preferences and objectives among stakeholders involved in historic building retrofits. For instance, while many respondents prioritize the initial cost due to budget constraints and the immediate financial impact of retrofit decisions, others place a higher value on preserving the historic integrity of the building, emphasizing minimal intervention and the conservation of cultural heritage. In addition, some stakeholders are primarily focused on improving thermal performance and energy efficiency, aiming to reduce operational energy costs and enhance occupant comfort. By clustering the solutions, we can more clearly delineate these varying retrofit aims and better understand the trade-offs between cost, preservation, and thermal quality. This stratification not only provides a nuanced view of the decision-making process but also facilitates the development of targeted strategies that address the specific needs and priorities of different groups, ultimately leading to more balanced and informed retrofit solutions.

As highlighted earlier, the primary limitation for tenants considering retrofits is the initial cost. To address this, the Pareto front solutions were clustered using the K-means cluster algorithm. In this study, the solutions were categorized into four clusters.

6.4.1. Cluster 1 (red points in Figure 5B)

This group prioritizes minimizing heating and cooling loads and enhancing thermal comfort without considering cost constraints. The representative solution, Generation 30, Solution 3, achieves total loads of approximately 5,418 kWh, with PMV values of −1.55 (summer) and 0.9 (winter). However, this comes at a high initial cost of 112,797 CNY.

6.4.2. Cluster 2 (blue points in Figure 5B)

This cluster represents the most balanced trade-off between the three objectives of energy efficiency, cost, and thermal comfort, as mentioned above. The core solution is Generation 30, Solution 4.

6.4.3. Cluster 3 (green points in Figure 5B)

Cluster 3 focuses on minimizing costs. The core solution, Generation 33, Solution 14, has a total cost of just 8,984 CNY. This scenario results in heating and cooling loads of 8,119 kWh, with PMV values of 0.84 (summer) and −2.48 (winter).

6.4.4. Cluster 4 (yellow points in Figure 5B)

It also emphasizes cost reduction but with slightly higher performance than Cluster 3. The representative solution, Generation 23, Solution 7, has a total cost of 13,149 CNY, heating and cooling loads of 9,395 kWh, and PMV values of 1.01 (summer) and −2.0 (winter).

Clusters 3 and 4 offer significantly lower costs compared to other scenarios, making them more feasible options for stakeholders with limited budgets. These solutions balance basic energy efficiency improvements and cost constraints, ensuring practical retrofit recommendations for tenants. Table 5 summarizes the
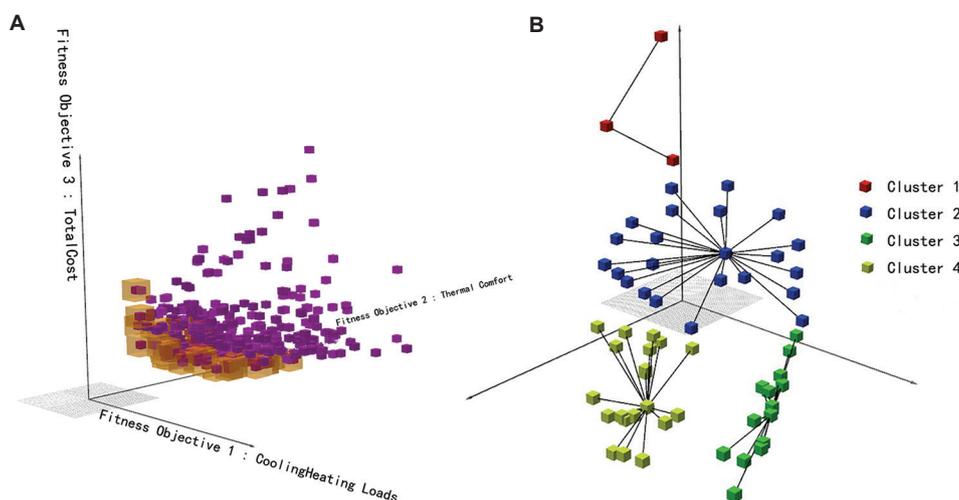
Figure 5. The distribution and clusters of the solutions located in Pareto front. (A) The pareto front; (B) the k-means cluster algorithm on the solutions.

Table 5. The priority measures for core solution of various clusters

Components	Original	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Exterior wall insulation	-	PU with a thickness of 0.25 m	Glass wool with a thickness of 0.05 m	Glass wool with a thickness of 0.05 m	Perlite with a thickness of 0.05 m
Roof insulation	-	PU with a thickness of 0.30 m	Glass wool with a thickness of 0.30 m	Rockwool with a thickness of 0.05 m	SXPS with a thickness of 0.06 m
Windows	-	6G+12A+6G+12A+6G	6Low-e+12A+6G+12A+6G	6G+12A+6G+12A+6G	6G+12A+6G
Air-tightness	-	0.0001	0.0001	0.0001	0.0001
Cooling and heating (kWh)	12,474	5,418	6,574	8,119	9,395
Thermal comfort (summer/winter)	1.74/−2.74	1.55/0.9	−1.71/1.25	0.84/−2.48	1.01/2.0
Initial cost (CNY)	0	112,797	46,401	8,984	13,149

proposed measures from various clusters. The insulation under Clusters 3 and 4 is relatively cheap and thin in thickness comparing with Clusters 1 and 2. The initial cost of these two scenarios can satisfy the requirements of the landlords.

However, recognizing that a modernization proposal should extend beyond merely categorizing retrofit scenarios, our study also integrates considerations for upgrading modern building systems in heritage contexts. For instance, additional modernization elements such as advanced control systems for HVAC operations, smart metering, and dynamic shading solutions are discussed as complementary measures that could be layered onto the core retrofit strategies. These proposals, though not fully quantified in the current analysis, indicate potential avenues for future research and implementation that align with sustainable building management practices.

7. Conclusion

The sustainable retrofit of heritage buildings in Suzhou presents a complex challenge that requires balancing historical preservation with the need for modern energy efficiency and environmental comfort. Through this study, the retrofit strategies have been identified that can address these challenges while maintaining the architectural and cultural integrity of Suzhou's historical buildings. The research highlights the following key points:

1. *Historical preservation.* The importance of preserving the unique architectural features and cultural significance of Suzhou's heritage buildings cannot be overstated. Retrofit strategies must be carefully designed to ensure that they do not compromise these aspects.

2. *Prioritized strategies.* Based on the simulation result of Pareto front, there is no need for extra insulation material on floor, and the suggested retrofit measures

3. *Cost-effectiveness.* While the initial costs of retrofitting can be high, this research also proposes strategies under budget constraints.

4. The integrated multi-objective optimization framework (using NSGA-II) effectively balances historical preservation, energy efficiency, cost reduction, and improved environmental comfort.

The sustainable retrofit of Suzhou's heritage buildings requires a multidisciplinary approach that respects the past while embracing the future. By incorporating advanced analytical tools such as space syntax and machine learning, alongside a deep understanding of historical preservation principles, we can develop comprehensive retrofit strategies that enhance energy efficiency, environmental comfort, and life-cycle cost. This research provides a foundation for future efforts, offering a roadmap for achieving sustainable urban development that honors and preserves the rich cultural heritage of Suzhou.

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Conflict of interest

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Availability of data

Data are available from the corresponding author upon reasonable request.

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