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Energy-Efficiency Retrofitting Strategies for Existing Residential Building Envelope System—A Case Study in China

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Abstract

With the rapid development of urbanization, the Chinese government has put equal emphasis on construction and retrofitting. But those projects did not achieve optimal effect because of the lack of targeted and systematic design guidance system. In this study, it first analyzes existing retrofitting methods and sorts into five retrofitting types as a basis, and then, captures the combinations and permutations of retrofitting methods and materials by parts and layers to build a database. After that, it combines different kinds of approaches by hierarchical matrix method to conclude the most efficient strategy. This study also selects typical residential buildings built between 1980 and 2000 in cold climate area of Northeast China as the research objects to test the integrity and effectiveness. As the results of this paper, it provides systematic guidance and multiple performance-based retrofitting strategies of the existing residential envelope system, which can improve indoor thermal comfort with low energy consumption.

Keywords

Existing Residence, Envelope System, Hierarchical Method, Retrofitting Strategy

1. Introduction

With China's urbanization exceeding 53% [1], the huge amount of housing stock accounts for more than three-quarter of the existing building, which consumes a lot of fossil fuel to meet the new standards of building performance. It is difficult to balance the thermal comfort and energy conservation, especially in the cold area. The energy-retrofitting of the envelope system accounts for 30% of the contribution of achieving the energy-saving goals [2]. Therefore, the performance-based retrofitting of envelope system has huge economic and environmental effects. At present, most of the retrofitting practice lacks basic data, energy-efficiency design at the early-design-stage, and evaluation standards, which leads to fuzzy results and optimal transformation effects. It is imperative to carry on energy-efficiency retrofitting on building envelope system to improve living quality and physical conditions of residential building.

Based on above problems, existing residential buildings built between the 1980 and 2000 in Northeast China are regarded as research objects, because of the intact and unified masonry construct, low construction standards, high energy consumption, and poor thermal performance. This study first captures the combinations and permutations of retrofitting methods and materials by parts and layers to build a database. Then, it focuses on combining the individual component retrofitting approaches in simulation tool to solve the compatibility of the whole envelope system and improve energy efficiency in retrofitting project. The result of this study can provide designers and related practitioners with new ideas and effective design-related decision-making strategies.

Literature review, field investigation and analysis, comparative analysis, and case analysis are also included. **Figure 1** summarizes the structure of this paper.

2. Background of Residential Building Retrofitting

The existing research includes five parts: theory, approach, effect evaluation, retrofitting component, and construction process.

John Habraken [3] first articulated Open Building Theory which is the basis of Four Layers [4] and Six Shearing Layers of Change [5]. The development of Brand's Shearing Layers is the Adaptive Future [6] which conducted a set of surrounding layers that explain how a building and its constituent parts will change over time. Fan Yue [7] conducted research on the improvement of existing residential quality from functionality, comfort and locality.

Studies on retrofitting approach mainly based on case study by summarizing methods and technologies, such as summarizing the design methods, processes and funding sources [8]; constructing an information-based auxiliary system for

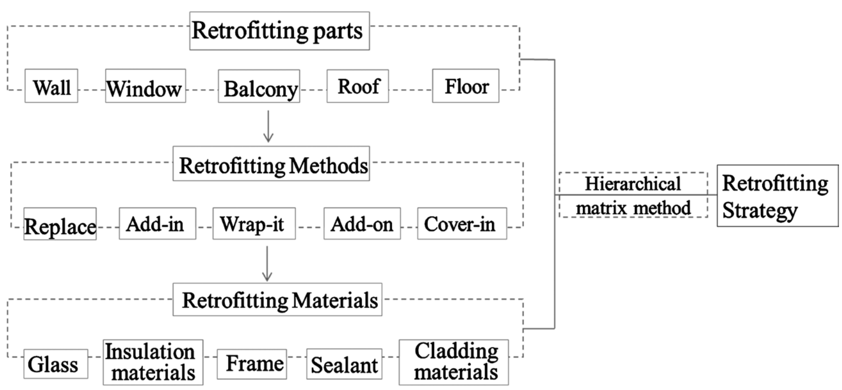


Figure 1. Research structure.

residential pathology diagnosis and repairing [9]; establishing a double-layer interface and consensus interval technologies [10]. Although researches on retrofitting approaches which summarized by the practical cases can be a reference, it lacks pertinence and specificity model which have not formed a comprehensive and systematic strategy database for the complexity and diversity of existing buildings.

Most of the research on the retrofit effect focuses on the energy consumption reduction of individual components [11] [12]. For example, Cui [13] compared energy reduction of two conditions from the energy-saving renovation of windows during a year. Zhu [14] researched on the development of windows and balconies with structural waterproof and thermal insulation properties Module. Without overall coordination with other parts in the entire enclosure system, those strategies can only improve the energy-saving effect at a certain extent.

Energy consumption of air conditioning and maintaining indoor thermal comfort accounts for about 50% of the total energy consumption [15]. Therefore, energy-retrofitting of the envelope system is an effective measure to improve indoor comfort and physical performance [16] such as improving insulation, reducing thermal loss, and solving cold bridges. A large number of studies have shown that it can effectively reduce energy consumption and improve energy-efficiency [17] [18] by improving the insulation performance of wall [19] [20], door and window [21], roof [22] and corridor.

In terms of the construction process and effect evaluation, Häkkinen [23] proposed to use the computer-aided simulation for performance evaluation before carrying out construction transformation, which avoided the uncertainty of detection during operation.

It is shown that most of the existing residential building retrofitting studies based on practical cases and focus on individual component, lacking a comprehensive retrofitting approaches system for the entire envelope system. It is necessary to build a functionality database of envelope system that is suitable for different building conditions of the huge amount of housing stock to reduce energy consumption of maintaining thermal comfort.

3. Retrofitting Strategy of Existing Residential Building

3.1. Retrofitting Parts and Layers

According to the hierarchical approach, the envelop system is divided into five layers, including wall, window, roof, balcony, floor, each of which can be divided into more specific layers. For example, the wall and the roof can be divided into exterior surface layer, performance layer, structural layer and interior surface layer hierarchically. The floor includes interior surface layer, performance layer and structural layer (**Figure 2**).

3.2. Retrofitting Strategy

Based on the different function of every layer, retrofitting approach can be catalogue and it compiles the existing retrofitting approaches into five categories (Table 1), which can be regarded as the basis to construct the hierarchical retrofitting strategies system. For example, the performance layer is embodied in improving the thermal insulation and waterproof performance of the envelop system.

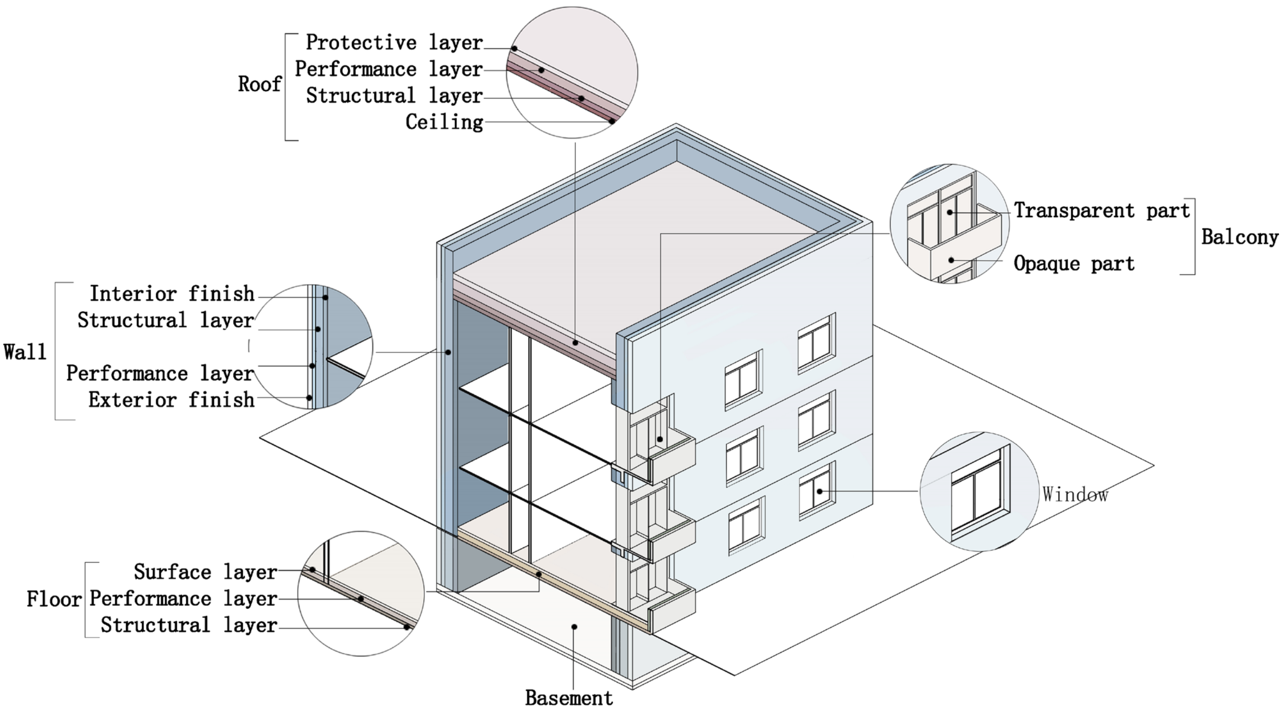
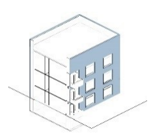
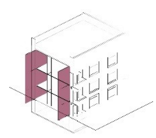
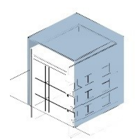
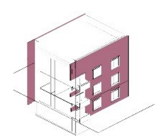
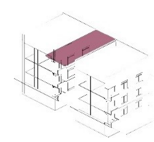


Figure 2. The parts and layers of the existing residential envelope system.

Table 1. Five retrofitting approaches of envelope system. [24]

	Replace	Add-in	Wrap-it	Add-on	Cover-it
Icon					
Approach	Remove the old envelope elements and replace with new one	Add new elements or materials inside envelope system	Wrap with the second façade, element with new material	Add new elements or materials on outside envelope system	Partially or fully covered courtyard or atrium
Example	Remove entire old envelope or individual elements, replace with new one	Internal thermal insulation; Box window	External insulation; Wrap the balcony with cladding layer; Second floor facade	Expand space; Additional stairs; New balcony	Partially or fully cover heated or unheated space
Advantage	Better performance; Eliminate the physical problems	Sufficient data support; Increase the thermal resistance	Solve thermal bridge Increase thermal resistance; New outer wraps; Little interference	New function Higher performance; Additional space	Establish thermal buffer; Improve natural ventilation; Additional space
Limitation	Great impact on occupant; Higher costs	Thermal bridge; Disturbance to indoor environment and occupant	Facade changes	Need to combine with other strategies; Structural constraints	Layout and function restrictions; Overheating risk

The five retrofitting approaches can be applied to different layers of the existing envelope system.

1) Wall

The wall is one of the most important components of the envelope system. It can be divided into four levels from outside to inside: exterior finish, performance layer, structural layer, and interior finish. Improving the performance of wall system can effectively reduce energy consumption that required to maintain the indoor thermal environment. It can be retrofitted by three approaches: Add-in, Replace and Add-on.

Add-in includes cavity insulation and internal insulation, applying for maintaining the original façade and monumental buildings, but it may affect indoor space and occupants living. Replace and Add-on can replace or repair the existing exterior finish to protect the performance layer (**Figure 3**), such as the combination of performance layer and exterior surface layer transforms to form external insulation or "ventilated vertical surface".

2) Window

As the transitional part between indoor and outdoor, the thermal loss directly caused by window accounts for about 23% - 27% of the total amount [25], and it affects the indoor thermal comfort, lighting, ventilation and sound insulation. The performance of the window is related to the performance of the frame, glass, heat transfer coefficient K, shading, air tightness, water tightness, and wind resistance.

The retrofitting approaches are Add-in, Replace and Add-on, including structure and materials. Add-in includes glazing upgrading and additional windows. Glass upgrading can improve performance by reinstalling high performance glass, such as Low-E glass and vacuum glass; additional windows are attaching single/double-glazed windows to the inside of existing windows to form the box window [26] [27]. Replace includes replacing the entire window with the double/three-layer window [28] of better performance and enlarging window. Add-on is to add fixed or adjustable sunshades to control solar gain and reduce cooling load according to different facade orientations.

3) Roof

The roof is an enclosure component that isolates adverse external environmental factors form the top of the building. It can be divided into exterior finish

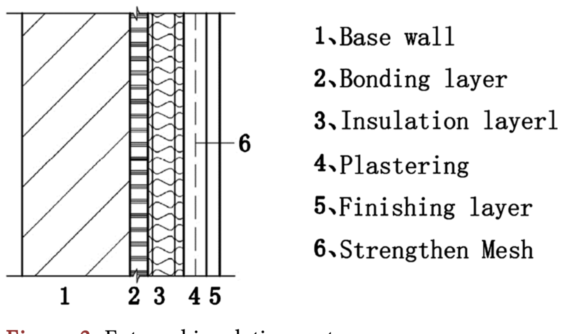


Figure 3. External insulation system.

layer, performance layer, structure layer, and an interior finish layer. The performance layer, including thermal insulation layer, isolation layer (divided into waterproof layer and vapor barrier layer), bonding layer, and leveling layer, is the key retrofitting layers. The retrofitting approaches include Add-in, Wrap-it, Replace, and Add-on. The performance layer is divided into slope roof insulation and flat roof insulation according. The slope roof insulation uses Add-in and Add-on to add an insulation layer between/above/below the rafters.

Add-in is to add loose materials between the top beams and slab to form a thermal insulation layer. Wrap-it adapts the transformation of flat roof insulation, including three methods: upright insulation, inverted insulation, removal and replacement of roof panels and roof systems. It can also use both Wrap-it and Add-on to combine performance layer and exterior surface layer [29], such as roofing green plants and flat slopes.

4) Balcony

The balcony is an extension of the internal space of the building. It can be divided into the transparent part (window) and the opaque part (balcony board) according structural. It can also effectively solve the balcony thermal bridge by solving the continuity between the balcony board and the floor.

The retrofit approaches of the balcony include Wrap-it and Replace to solve thermal bridges and form thermal buffer zones. The key to solving the thermal bridge is to transform the balcony board, such as using thermal insulation materials to cover the entire balcony board; removing existing balcony and installing thermal insulation on the edge of the balcony board and replace it with a new balcony to create a thermal fracture zone. The balcony with single-layer or double-layer aluminum frame glass to form a thermal buffer zone by Wrap-it. For the top floor balcony without horizontal shading, additional high-performance glass/window can be introduced and Add-on fixed or adjustable sunshades to improve the insulation performance of the transparent part.

5) Floor

The floor can be divided into interior finish, performance layer, and structural layer. The main retrofit layer, the performance layer can also be divided into bonding layer, isolation layer, leveling layer and insulation layer. Add-in and Wrap-it can be used to effectively reduce the thermal loss from the first floor, including add insulation at the top/bottom of the floor, and the use of pressure-resistant insulation materials. If there is underground space in existing building, the basement roof is used as a load-bearing component to separate the first-floor space and the basement space. A new performance layer is added on the top of the existing floor with insulation materials (**Figure 4(a)**). If there is no underground space, a new performance layer is installed at the bottom of the slab by adding insulation materials (**Figure 4(b)**).

3.3. Retrofitting Material

There are five materials types: thermal insulation materials, glass, frames, sealants,

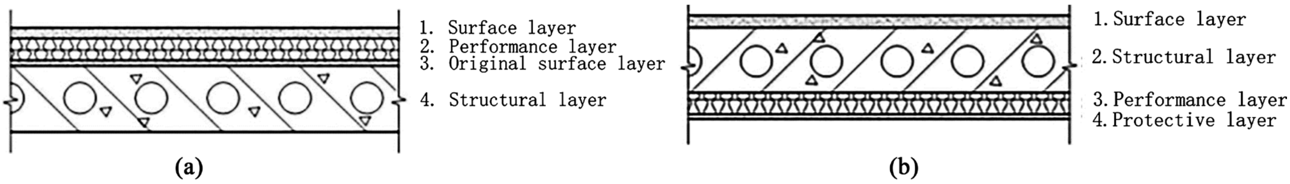


Figure 4. (a) Insulation added on the top, (b) Insulation added at the bottom.

Table 2. Retrofitting material

Material	Description	Requirements	Material type	
Thermal insulation materials	Materials with high thermal resistance and low thermal transmittance	Thermal insulation	Organic thermal insulation materials, Inorganic/mineral thermal insulation materials	
Glass	Transparent material with visual permeability	Thermal insulation, passive solar heat gain, shading	Thermal insulation glazing, Low-E coating, colored glass	
Frame	Assemble and organize glazing	Thermal insulation Air permeability	Wood Wood/aluminum Aluminum alloy	Steel, Polyvinyl Chloride (PVC) Unsaturated Polyester (UP)
Sealant	Seal gaps Prevent uncontrolled air and water flows	Thermal insulation Air tightness	Neoprene, EPDM, Flexible PVC, Silica gel	Rigid polyurethane Hot melt isobutylene polysulfide sealant
Facing and cladding materials	The final coat gives the final impression	Protect the inside layer of building, e.g. thermal insulation, air tightness	Gypsum board Topcoat Photocatalytic interior paint	Phase change material Cladding panel

and cladding materials, among which, thermal insulation materials and multi-layer glass are most important in performance improvement (Table 2). Thermal insulation materials are based on low thermal conductivity that isolates the air transformation [30] between different temperature zone. The selection of materials depends on the fire resistance, sound insulation, compressive strength, economy, constructability, environmental-friendly and application for different parts and layers.

There are some of the most common use materials including: a) organic thermal insulation materials: Expanded Polystyrene (EPS), Extruded Polystyrene (XPS), Polyurethane Rigid Foam (PU), Phenolic Foam (PF). b) inorganic/mineral with high recyclability, fire resistance and thermal insulation materials: mineral wool, rock wool, glass wool, foam mineral thermal insulation materials, aerogel [31]. In addition, the thermal resistance of the Vacuum Insulation Panel (VIP) [32] is about 10 times higher than that of the traditional polystyrene board of the same thickness, and the space restriction is very low, which is very effective in rebuilding projects.

Glass plays a key role in building performance, which provides a visual and light connection between outdoor and indoor and improves the quality of the indoor environment. The measurement index is the heat transfer coefficient K value and is influenced by the number of glazing layers, the depth of the cavity, the filled gas and the coating. The glass can be used in retrofitting includes: heat-absorbing glass, heat reflecting glass, multi-layer glass, Low-E glass, vacuum glass [33].

Upgrading of frame is mainly based on aluminum, plastic, steel and thermal bridge frames. Thermal bridge frame is a thermal insulation material that can be applied to window frame profiles specially to reduce thermal bridge including ABS (acrylonitrile-butadiene-styrene), polyethene HD, polyamide (Nylon), Polypropylene, PVC-U (polyvinyl chloride) and polyurethane. Sealant is also an important material to solve the airtight between the frame and glass, mainly including sealing strips and sealants.

Facing and cladding materials are the most directly in contact with the external condition. According to the project, budget, and expected effect, there are multiple approaches, such as cladding materials, including cement plastering that provides a hard protective with adhesives, and creating a cavity structure between the performance layer and the panel to form a ventilated facade; Gypsum board with strong water absorption, sound absorption and decoration; top paint with decoration and protection; Phase change material (PCM) [34] that can store or release energy.

4. Case Study

Hierarchical matrix editing method is introduced to catalogue design approaches, emphasizing the hierarchical progress in retrofitting process. It firstly formulates the hierarchical retrofitting database from the individual component retrofitting approaches. Then, transform the individual component system to the overall retrofitting strategies of the envelope system by layers, realizing the integration of technologies from single to diverse.

4.1. Case Introduction

This study has made field surveys and data collection work about existing residential building retrofitting in typical cities in the Northeast China. It is one of the eight earliest industrial areas in China, which has important historical, cultural and memory values. Since the early 1950s, it has been taking the lead in responding to various housing policies, and it was the place where housing design standards and implementation were first established. According to the preliminary survey carried out in typical cities in Northeast China, such as Shenyang, Harbin, Changchun and Dalian, the residential evolution of Dalian can profoundly reflect the social and economic changes in China. This study takes Building-21 of the 10th Group of Wencuixuan community, Dalian as an example. The hierarchical matrix editing method is introduced to solve the compatibility of individual components of different layers. Firstly, building-21 is divided into five layers by part (**Figure 5**). Then, a basic information database is established to form the first hierarchical editing layer (**Table 3**), including location, original information, current statue information, plan and *et al.*

4.2. Retrofitting Strategy

Based on the first hierarchical editing layer, collecting the corresponding retrofitting approaches of each layer to form the second hierarchical editing layer (**Table 4**).

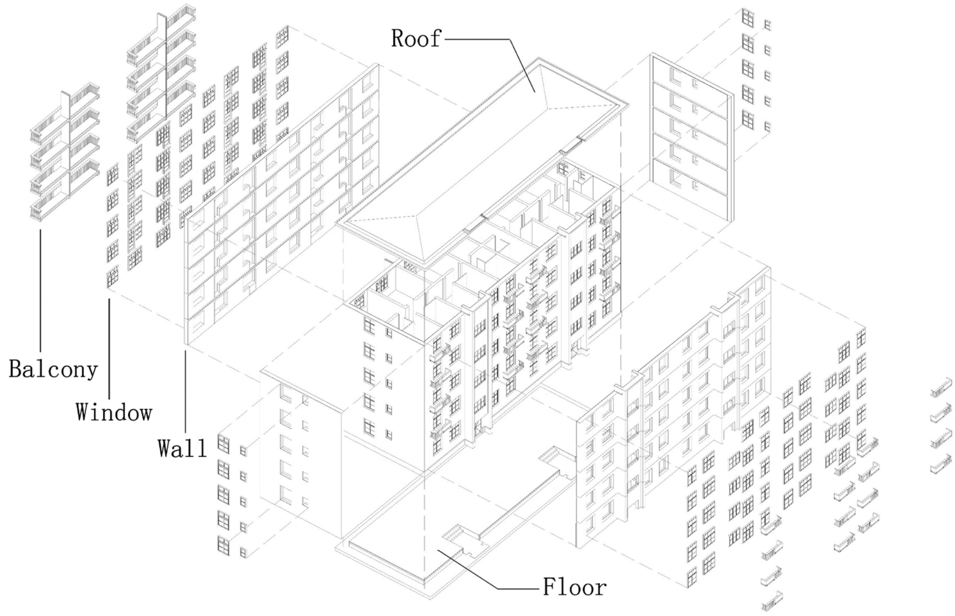
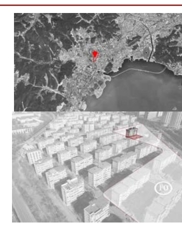
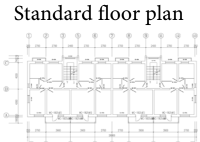
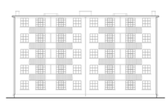
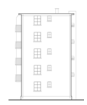


Figure 5. Layer of building-21 envelope system.

Table 3. The first hierarchical editing layer: Building-21 envelop system information survey.

Sample selection: Group-10, Building-21 Location: Intersection of Wuyi Road and Wenjing Street, Shahekou District, Dalian Construction year: 1981-1983 Scale: 20 households Total construction area: 1205 m^2 Terrain: gentle slope Construction company: Dalian Institute of Technology					
Standard floor plan  One-way split type Shape coefficient: 0.38		East facade  	South facade  	West facade  	North facade  
Window-to-wall		9%	21%	9%	21%
Envelope system	Wall	Form	Red brick wall without insulation		
		Layer	External finish coat: 10 mm 1:2.5 cement mortar overlay; Structural layer: 370 mm 75# red brick; Interior surface: 2 mm hemp knife white gray		
		Performance	Thermal resistance: 0.50 - 0.53 (m^2·K·W^{-1}); Thermal transmission: 2.68 - 3.61 (W·m^{-2}·K^{-1}) Solar radiation absorption coefficient ρs: 0.56 - 0.78		
	Window	Form	Single glazing, Double casement window		
		Layer	Glass: ordinary transparent glass; Frame: red and white mixed pine;		
		Performance	Thermal transmittance: 5.8 W/(m^2·K); Conductivity: 500 W/(m·K)		

Continued

Roof	Form	Precast concrete slab, slag insulation			
	Layer	Performance layer: 5 mm waterproof, 150 mm slag insulation Structural layer: 120 mm reinforced concrete precast slab Interior finish coat: 8 mm 1:3:9 cement-lime mortar, 2 mm hemp-fibred plaster			
	Performance	Thermal resistance: 0.64 ($m^2 \cdot K \cdot W^{-1}$) Thermal transmission: 3.2 ($W \cdot m^{-2} \cdot K^{-1}$)			
Balcony	Form	None	Independent board No insulation	None	Independent board No insulation
	Layer	Transparent part: double-layer casement wooden window; Opaque part: cement mortar finish			
	Performance	Thermal transmission of transparent part: 3.48 ($W \cdot m^{-2} \cdot K^{-1}$) Conductivity of opaque part: 500 W/(m·K)			
Floor	Form	Crushed stone and concrete floor, no insulation			
	Layer	External finish coat: 10 mm 1:2 cement mortar; 20 mm 1:3 cement mortar Structural layer: 150 mm crushed stone grouting 25# mixed mortar			
	Performance	Conductivity of opaque part: 2.43 W/(m·K)			

Table 4. The second hierarchical editing layer.

	Original state	Layer	Approach	Method
Wall	Red brick wall without insulation. 370 mm solid brick masonry wall Insufficient thermal resistance	Performance layer	Cavity insulation	Inject loose or foam thermal insulation materials into the existing cavity of the wall to increase thermal resistance. Performance depends on the depth of the wall cavity
		External finish coat	Repair/replace external finish coat materials	Use paint or stone to replace/repair the external finish coat to protect the performance layer
		Performance layer & External finish coat	Internal Insulation	Add gypsum board to internal finish coat to improve thermal resistance.
			External insulation	Attach a double-glazing on the inside
			Ventilated facade	Attached rigid thermal insulation board and cladding to external finish coat to improve thermal resistance.
Window	Single glazing, Double casement window Insufficient thermal performance and poor sealing	Window system	upgrade	Add double glazing and install on existing window frame
			The second single/double glazing	add a single/double glazing inside
			Replace	Replace window with triple glazing
		shading	Fixed shading	Shading devices on the outside of the window, such as hanging, fixed blinds.
			Adjustable shading	Adjustable shading devices on the inside or outside of the window, in the form of movable sun visors, blinds, etc.
		Space intervention	Enlarge windows	Enlarge original window and replace with new one
Roof	performance layer: insufficient insulation of precast concrete slab. Waterproof layer and leveling layer: insufficient thermal resistance	Performance layer	Asphalt insulation	Insulation between rafters and suspended ceiling to increase thermal resistance.
			Top floor insulation	Prevent thermal loss
		Performance layer & External finish coat	Flat floor insulation	Additional insulation and waterproof layer on the roof panel
			Green roof	Additional insulation layer, waterproof layer, soil and plants are provided on the roof panel
			Flat to slope roof	Add insulation on roof panel with hanging tiles to increase the thermal resistance

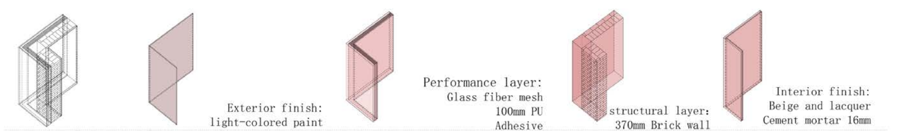
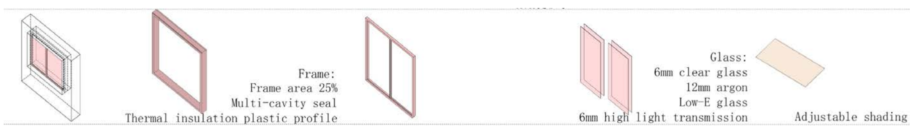
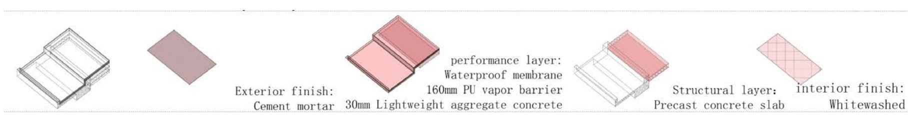
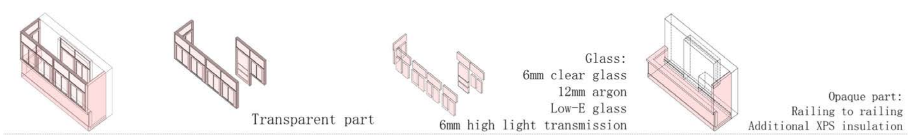
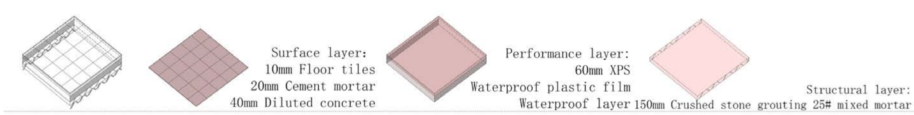
Continued

Balcony	Independent board without insulation: connected to the indoor floor with thermal bridge	—	Balcony board insulation	Add insulation on all balcony surfaces (top and bottom)
			Remove/replace balcony	Remove existing balcony and install insulation on the edge of the floor
			Wrap	Covered with single/double glazing and aluminum frame
Floor	Gravel concrete floor without performance layer. No insulation Sever thermal loss	Performance layer	Insulation on top pf Floor/basement	Add insulation on all balcony surfaces (top and bottom)
			Bottom insulation of basement ceiling	Add thermal insulation on the bottom of floor slab to increases thermal resistance

Table 5. The third hierarchical editing layer.

	Original state	Retrofitting strategies				Space intervention
Wall	Brick-concrete structure without insulation	Cavity insulation	Internal insulation	External insulation	Replace/repair exterior finish coat	Ventilated facade
Window	Single-layer glazing, wooden frame, no seal	Second single/double glazing	Replace with double/triple glazing	Fixed shading	Adjustable shading	Enlarge hole
Roof	Insufficient insulation	Asphalt insulation	Top floor panel insulation	Flat roof insulation	Green roof	Flat to slope roof
Balcony	Unclosed balcony, independent board, no insulation	Balcony board insulation	Remove/replace balcony	Covered with single glazing	Covered with double glazing	
Floor	Crushed stone concrete floor, no insulation	Insulation on top of floor panel	Insulation on bottom of floor panel			

Retrofitting strategy icon

Layer	strategies	icon
Wall	External insulation	
Window	Double layer glazing	
Roof	Upright flat roof insulation	
Balcony	Wrap double glazing	
Floor	Add insulation on the top	

Then, carry a comparison study with the integrity and effectiveness of the combination of individual components retrofitting approaches to form different strategies. The most efficient strategy can be selected according to simulation results to form the third level matrix editing (Table 5). The three hierarchical systems proceed in sequence, systematically formulating an efficient retrofitting strategy to the systematically overall system.

5. Conclusions

This paper first divides the envelope system into five parts and several structural layers, and then, sorts out existing residential retrofitting approaches into five types by parts. The hierarchical method is introduced to form a systematical database of existing building retrofitting strategy. On the one hand, it can improve indoor thermal comfort with lower energy consumption. On the other hand, it expands the basic information data of the existing residential envelope system in the cold climate area in China. The database can help designers make retrofitting-related decision and choose retrofitting strategies at early-design-stage efficiently. It also establishes a system for the evaluation and comparison of the building performance.

However, this study only investigated a few typical cities in cold climate area, and the scope of the study needs to be expanded. Therefore, follow-up studies will adopt a variety of data collection methods to more accurately collect the current status of the envelope system, and carry out more interdisciplinary research to improve accuracy. Simulation tools are also introduced to make evaluation and comparison.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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