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Review

Sustainable-Driven Renovation of Existing Residential Buildings in China: A Systematic Exploration Based on Review and Solution Approaches

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Abstract: Under the backdrop of China's national strategy to achieve carbon neutrality by 2060, efforts are underway across governmental, corporate, societal, and individual sectors to actively explore energy-saving renovations in existing buildings. Given that residential buildings constitute a significant proportion of the total energy consumption throughout the lifecycle of buildings in China, sustainable renovation of residential structures can contribute significantly to implementing China's carbon emission reduction policies. While there exists a plethora of technological means in the market aimed at improving the energy performance of residential buildings, there still needs to be a more systematic discussion on the framework for sustainable renovation of existing Chinese residential buildings, with knowledge dissemination still needing to be more cohesive. In this context, this paper provides a comprehensive review of the field, utilizing bibliometric methods. Through a systematic review of selected peer-reviewed literature from the Web of Science and Scopus databases, the study focuses on the sustainable renovation of existing Chinese residential buildings, categorizing the process into three main stages: sustainable renovation, building performance simulation and suitability assessment. The paper also reviews the research methods adopted by previous researchers in the renovation, simulation and assessment stages, considering various optimization algorithms, variables, objectives, and software tools. Subsequently, the paper synthesizes a research framework comprising these three stages combined for different research objectives, aiming to assist policymakers, designers, and researchers in gaining a comprehensive understanding of the implementation status of sustainable renovation in existing Chinese residential buildings, identifying barriers to implementation, and formulating more efficient renovation policies and strategies for the future.

Keywords: existing Chinese residential buildings; sustainable retrofitting; building performance modeling; suitability assessment

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1. Introduction

Over the past two decades, greenhouse gas emissions have consistently been recognized as one of the primary drivers of the climate crisis, with the building industry garnering significant attention due to its notable impact on greenhouse gas emissions and energy consumption [1]. Globally, buildings account for approximately 40% of energy use and 33% of greenhouse gas emissions [2,3]. According to statistics from the China Association of Building Energy Efficiency (CABEE), in 2021, the entire lifecycle energy consumption of buildings in China represented 36.3% of the total national energy consumption and 38.2% of carbon emissions, as illustrated in Figure 1. This underscores the fact that the building sector has become one of the most significant areas of energy consumption, not only in China but also globally. However, it is anticipated that in the future, buildings will continue to be a dominant factor driving growth in energy demand.

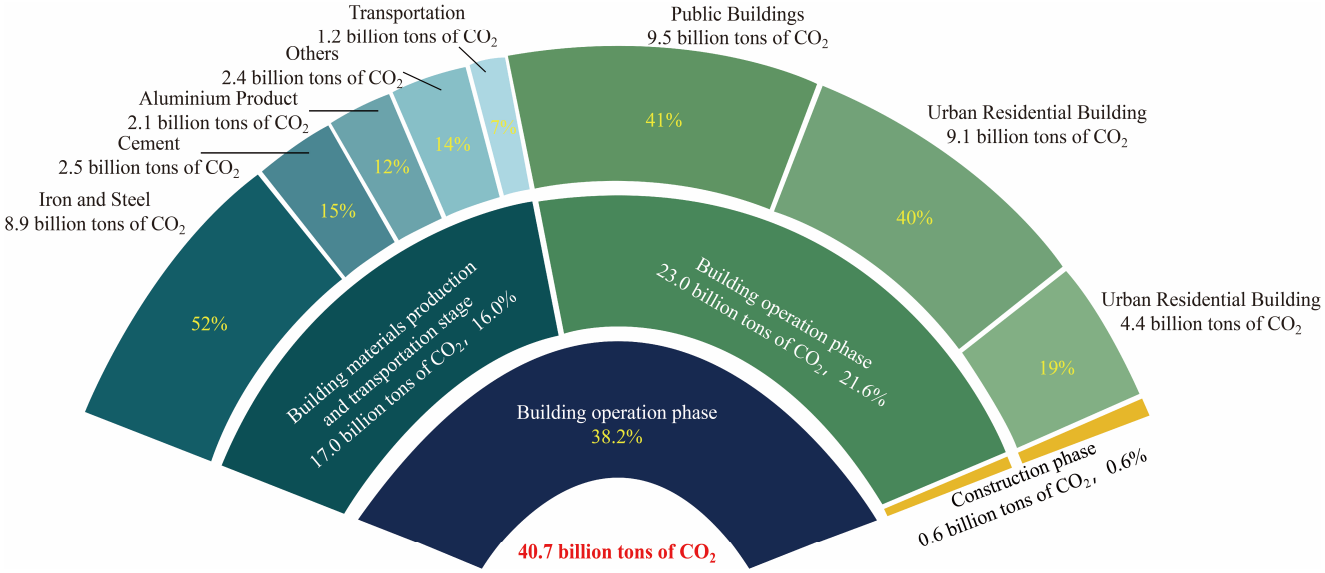


Figure 1. Carbon emissions in the whole process of housing construction in China in 2021. (The carbon emissions of building materials and construction in the construction phase only include housing construction, not infrastructure; The carbon emission of building materials is only energy carbon emission, excluding the carbon emission of the industrial process of building materials; Energy-related carbon emissions in China total 10.6 billion tons of CO_2, according to the International Energy Agency).

In this context, energy conservation and emission reduction from the perspective of the architectural sector have become a global consensus. Many countries and regions have successively formulated development plans and supporting policies to achieve energy conservation and emission reduction. Among them, the European Union has mainly relied on the Energy Efficiency Directive (EED) 2012/27/EU and the Energy Performance of Buildings Directive (EPBD) 2010/31/EU over the past fifteen years to improve the energy performance of buildings [4,5]. In 2023, the EPBD was revised to better achieve its energy-saving goals [6]. Additionally, in 2019, the European Union proposed the "Green Deal", aiming to reduce its greenhouse gas emissions by 55% by 2030 and achieve carbon neutrality by 2050 [7]. These initiatives will make significant contributions to energy conservation and emission reduction in the architectural sector.

For many years, the Chinese government has been committed to formulating and implementing top-down energy-saving measures [8]. In the "Twelfth Five-Year Plan" and "Fourteenth Five-Year Plan", energy-saving renovations in buildings were explicitly identified as critical areas, leading to a series of transformations: from energy-efficient buildings to green buildings, from individual buildings to regional constructions, and from "shallow green" (emphasizing local improvements, weakening overall integrity) to "deep green" (emphasizing ecosystem interactions and dependencies). However, most laws and regulations focus on new constructions [9]. In recent years, the Chinese government has proposed a series of new priorities, including clean energy and new urbanization, to promote the development towards carbon neutrality goals [10]. Sustainable renovation of residential buildings will contribute to implementing China's carbon emission reduction policies. In 2021, urban residential buildings accounted for 40% of the total lifecycle energy consumption of buildings in China, while rural residential buildings accounted for 19%, as shown in Figure 1. Against the backdrop of global climate change and environmental degradation, the Chinese government has prioritized improving residential building energy efficiency as a critical agenda in its national decarbonization policies for the building sector [11].

Figure 2 displays the chronological development of energy retrofitting in the construction industry of China and the European Union, highlighting key policies and advancements in energy efficiency.

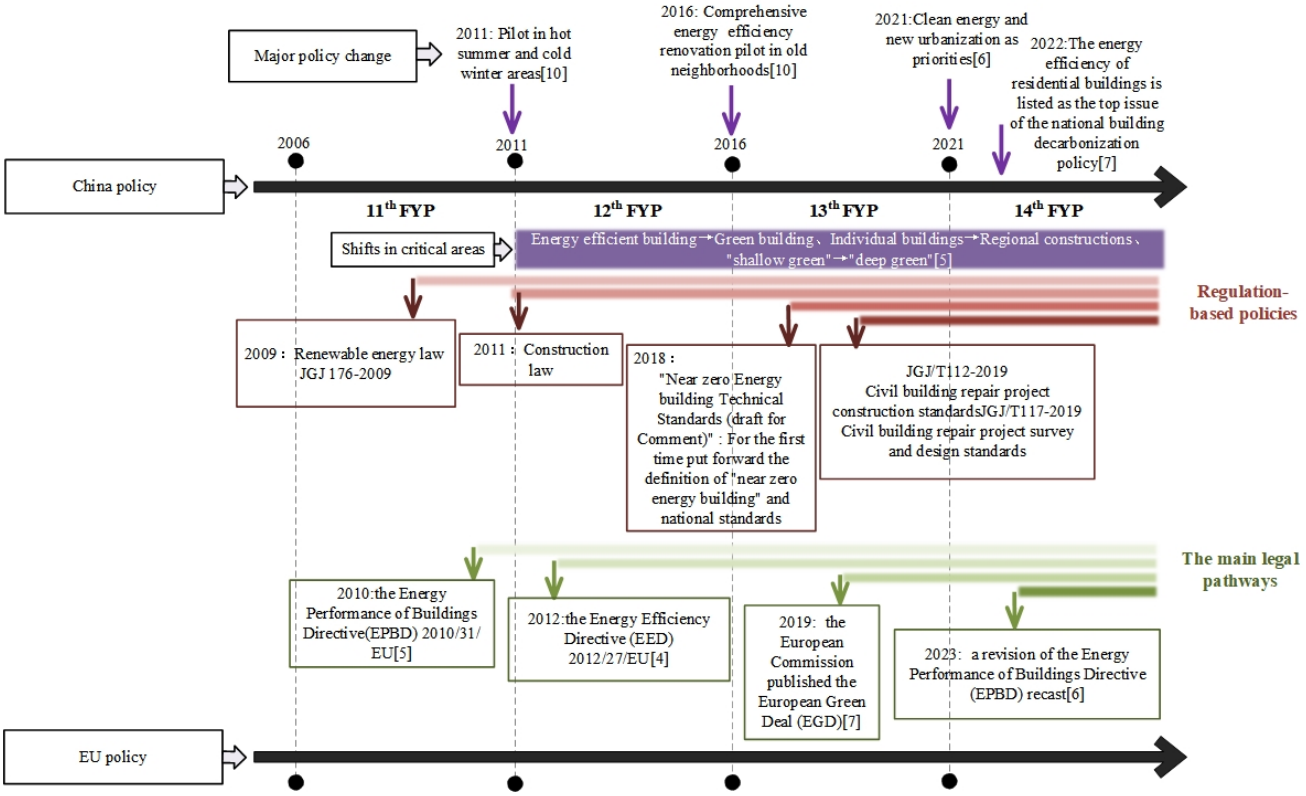


Figure 2. Chronological Timeline and Key Policies in the Development of Energy-Efficient Renovations in the Construction Sectors of China and the European Union (Information from official documents and other literature).

The scope of this study encompasses the sustainable renovation framework for existing residential buildings in China, which are defined as buildings still used for residential purposes, including mixed-use commercial, residential properties, and specific historic residential structures. A considerable proportion of residential buildings today were not constructed with a prominent focus on energy efficiency during the building phase, failing to meet current standards and resulting in significant resource wastage [12]. As an increasing number of residential buildings approach the end of their lifecycle, various risks related to material durability are emerging, including but not limited to the degradation of insulation layer structures and deformation of door and window components. These issues significantly diminish the thermal insulation performance of building structural components, exacerbating energy consumption concerns. Consequently, the renovation of residential buildings may be not only in environmentally abnormal areas but also in a more significant proportion of existing old buildings.

In the past, urban renewal often prioritized demolition and replacement with new construction. However, considering the changes in national and global policies and the magnification of problem scales, there are more viable options to address the challenges of low energy efficiency and structural defects by replacing existing residential buildings. This approach would have severe repercussions on current urban structures and society and would be financially and environmentally unsustainable [13]. Instead, a more feasible approach is to prioritize extending the lifespan of existing residential buildings through maintenance, repair, and renovation. Given the large number of buildings requiring upgrades, the scale and investment required for renovation projects are significant. Therefore,

existing residential buildings possess substantial energy-saving and emission-reduction potential, and the renovation sector will continue to receive increasing attention.

Numerous researchers have delved into the application and development of residential building sustainable renovations from various perspectives, including relevant policies, research dynamics, and technological advancements in energy-saving renovations [14–17]. Among these studies, Italian scholars have notably contributed a significant number of papers on the theme of residential building sustainable renovations. In contrast, research and practice by Chinese scholars in residential building sustainable renovations remain relatively limited, particularly in systematic discussions on energy-saving renovations for sustainable Chinese residential buildings [14]. The knowledge base in this area still needs to be more cohesive.

The existing research gap highlighted above necessitates a comprehensive and systematic overview and a critical analysis of sustainable renovations for existing Chinese residential buildings. This study aims to provide theoretical guidance and targeted recommendations for the establishment of a framework for sustainable renovation measures in existing residential buildings in China and the formulation of feasibility plans.

2. Methods

This study is based on the PRISMA framework [18] and systematically reviews the research trends regarding sustainable renovations of past residential buildings in China. Literature data were primarily retrieved from two major databases, Web of Science (WOS) and Scopus, as these databases are widely used global search engines for peer-reviewed literature, covering almost all studies related to sustainable renovations of residential buildings in China. This approach greatly minimizes biases caused by different databases in the field. Additionally, Google Scholar was used as a supplementary search engine to ensure comprehensive coverage.

The complete search character consists of three parts:

(1) It restricted the search to "existing buildings".
(2) It focused on the Sustainable Retrofit of Residential Buildings.
(3) It limited the research geography of the search to China.

Taking WOS as an example, the advanced search utilized Boolean terms such as "(existing build* OR existing architect*) AND (resident* OR dwelling OR house) AND (Energy retrofit OR sustainable retrofit OR green retrofit) AND (china)" within the subject (title, abstract, keywords) to perform a literature search.

The search was conducted on 26 February 2024, without restricting the time range or publication sources, aiming to minimize potential publication bias [19]. The initial search retrieved 368 documents, 110 from WOS and 258 from Scopus. These documents underwent a preliminary screening using the database' s automated filtering function (Table 1). Exclusions were made for documents not openly available due to accessibility issues, those in languages other than English (to avoid potential misunderstandings in translation), and publications in non-peer-reviewed journals (which could not serve as representative examples of high-level scientific research). After eliminating duplicates, 274 documents remained.

Subsequently, a two-stage manual screening process was employed to identify relevant literature. In the first stage, titles, abstracts, and author keywords were assessed to narrow the scope to existing residential buildings, energy retrofitting, sustainable renovation, or green renovation within the context of China. This stage yielded a total of 131 documents. Suppose the relevance of a document could not be determined solely from the title; a full-text assessment was conducted in the second stage to determine its relevance to the topic. Ultimately, 85 documents were selected for detailed review and analysis.

Figure 3 illustrates the PRISMA flowchart employed to screen the literature and conduct the systematic evaluation in this study.

Table 1. Inclusion and exclusion criteria for the literature selection.

Inclusion	Exclusion
Full-text available	Full text not available
English	Non-English
Peer-reviewed journals	No peer-reviewed journals
Topics: (existing build* OR existing architect*) AND (resident* OR dwelling OR house) AND (Energy retrofit OR sustainable retrofit OR green retrofit) AND (China)	Does not correspond to the mentioned topics

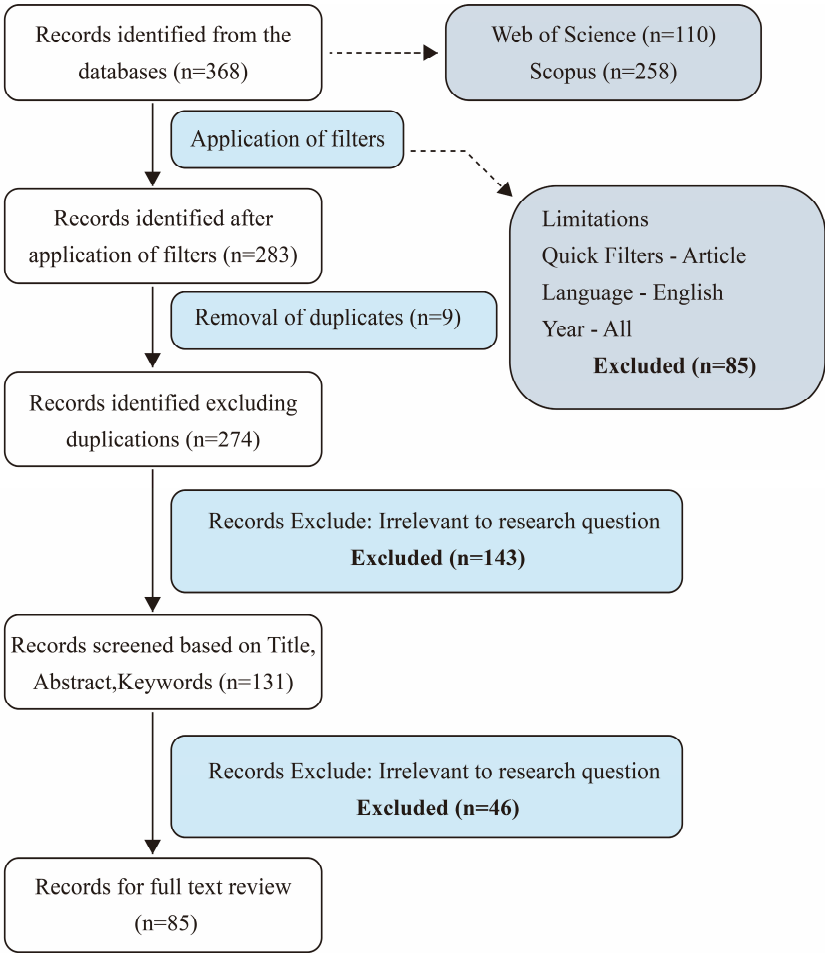


Figure 3. PRISMA flowchart of the search and selection process.

3. Results and Discussion

3.1. Mainstream Research Trends

As depicted in Figure 4, the literature selection focused on publications from 2009 onwards (over the past 15 years), with a Compound Annual Growth Rate (CAGR) of 6.3% from 2009 to 2023. A minor peak in publication occurred in 2009, attributed to building energy efficiency being identified as one of the ten critical projects for enhancing efficiency in the "Eleventh Five-Year Plan" (2006–2010) [20,21]. During the period from 2017 to 2018, the growth rate was most significant, reaching 200%, while the number of publications increased by seven articles from 2020 to 2021, representing the most notable increase in quantity. This indicates a significant increase in China' s research on sustainable renovation of residential buildings since 2018, reflecting a clear upward trend with a growth rate of 650%, demonstrating a strong interest in this topic within the architectural research

community. The publications peaked in 2022 and then experienced a slight decline over the past two years.

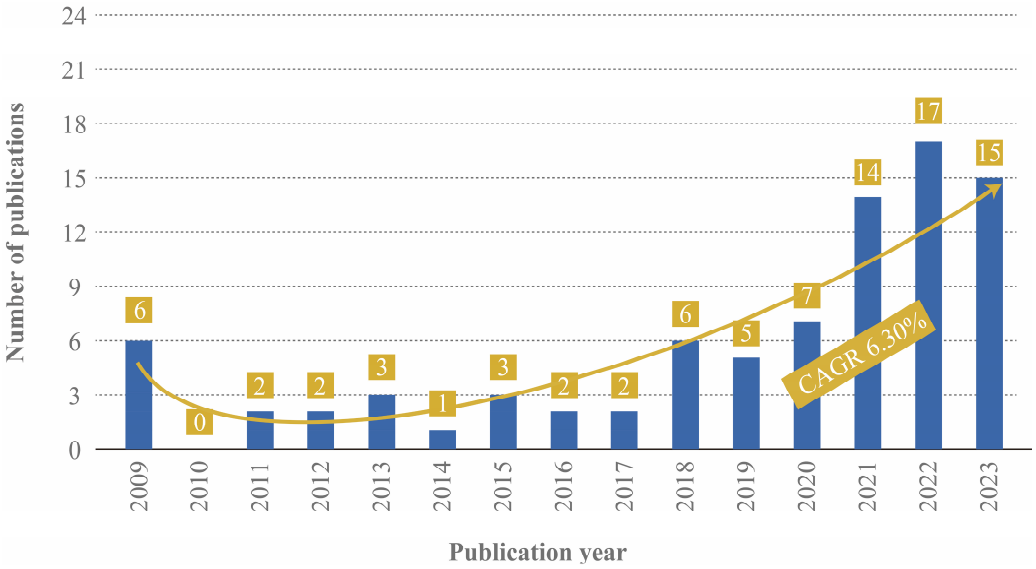


Figure 4. Publication of analyzed studies in the last 15 years (2009–2023).

To explore the underlying reasons for the changes in the publication quantity curve, a review of the literature and official government documents was conducted for the four critical years mentioned (including the heterogeneous year 2009, the year with the most significant growth rate in 2018, the year with the highest growth quantity in 2021, and the year with the highest quantity in 2022). As shown in Figure 2, the heterogeneous nature of the quantity in 2009 may be attributed to the enactment of the Renewable Energy Law by the Chinese government, which standardized energy-saving renovations through official documents. After 2011, the field of energy-saving renovations transitioned from "light green" to "deep green", achieving high-quality transformation, and the quantity curve entered a period of smooth growth. In 2018, China's Ministry of Housing and Urban–Rural Development (MOHURD) first released the national standard "Technical Standard for Nearly Zero Energy Consumption Buildings (Draft for Solicitation of Comments)". This was China's first technical standard formulated explicitly for the concept of "nearly zero energy consumption buildings", defining the concept and control indicators for the first time. This propelled the energy-saving renovation field, which had been developing for many years, into a period of rapid growth. During the 14th Five-Year Plan period of rapid growth, the Chinese government introduced a series of new priorities, including promoting clean energy and new urbanization in 2021. In 2022, the Chinese government prioritized improving the energy efficiency of residential buildings as the primary topic of the national decarbonization policy for the construction sector. This can explain why the publication quantity peaked in 2022.

Figure 5 illustrates the geographical distribution of studies included in the review. Due to significant differences in building characteristics, economic conditions, and climatic conditions across China, the appropriate renovation methods for residential buildings often need to be differentiated based on five major climatic regions: severe cold, cold, hot-summer, and cold-winter, hot-summer, and warm-winter, and temperate regions. The zoning criteria are outlined in Table 2. Figure 6 depicts that energy retrofitting of residential buildings in China is concentrated in areas with severe cold, cold, and hot-summer and warm-winter climates. This is because regions with severe cold and cold climates typically exhibit high energy consumption during winters due to district heating systems, offering significant energy-saving potential. In hot-summer and warm-winter regions, large temperature variations between seasons necessitate considerations for both heating

and cooling technologies, making optimization measures equally promising. Conversely, regions with hot summer and warm winter climates primarily consume energy for summer cooling, resulting in relatively lower energy-saving potential. Additionally, equipment optimization aims to improve indoor thermal comfort in mild regions where the climate is suitable without heating or cooling.



Figure 5. China's five major thermal design climate regions and their indicators.

Table 2. Thermal zoning index.

Climate Zone	Mean Monthly Temperature	
	Coldest	Hottest
Severe Cold	≤−10 °C	≤25 °C
Cold	−10–0 °C	18–28 °C
hot summer and cold winter	0–10 °C	25–30 °C
hot summer and warm winter	−10–0 °C	25–29 °C
Temperate	−10–0 °C	18–25 °C

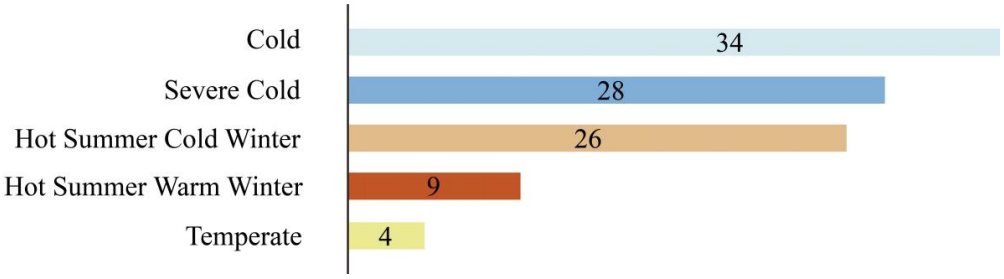


Figure 6. The number of times in each climate zone in the literature reviewed.

3.2. Mainstream Research Framework

This study aims to identify the optimal path for sustainable renovations of existing residential buildings in China, serving as guiding principles for the renovation process from a theoretical and practical perspective to inform practice. Upon detailed examination of the literature obtained in the second stage, it was found that sustainable renovation of residential buildings is a complex process, broadly summarized into three stages: sustainable renovation, building performance simulation, and suitability assessment.

3.2.1. Sustainable Transformation in Different Climate Zones

During the review, it was found that sustainable renovation measures for existing residential buildings are widely considered to involve several main systemic approaches:

wall systems, windows and shading systems, roof systems, heating, ventilation, and air conditioning (HVAC) systems, as well as lighting systems. As depicted in Figure 7, these can be categorized into building envelope retrofit and building equipment system retrofit. Energy Management Systems (BEMS), computer-based control systems capable of real-time monitoring and controlling building energy consumption, play a crucial role. To achieve effective energy management and optimization, BEMS can integrate various building equipment and control systems, such as heating, ventilation, air conditioning, and lighting [22]. It is important to note that specific retrofit measures should be tailored to the characteristics and requirements of the building. Additionally, cost-effectiveness and feasibility should be considered during the renovation process to ensure the retrofit measures' implementation effectiveness and economic benefits [23].

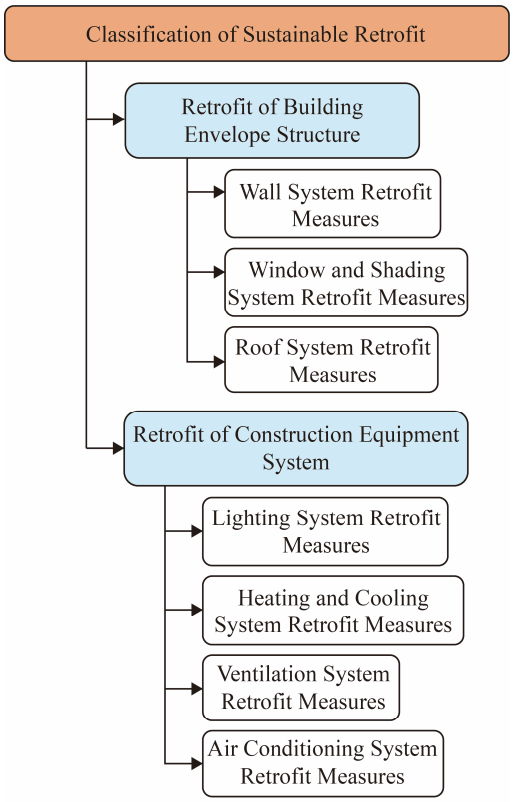


Figure 7. Classification of sustainable retrofit directions.

- Wall system retrofit program

The exterior wall constitutes the most significant portion of a building's envelope structure, with heat loss through the exterior wall accounting for approximately 30% of total heat loss. Therefore, enhancing the insulation performance of exterior walls is one of the most effective retrofit measures for all four typical residential building types [24]. Adding insulation layers to exterior walls is much more cost-effective than replacing external windows and yields better energy-saving effects [25,26]. Materials such as gypsum boards or insulation boards can enhance the thermal insulation performance of walls [27,28]. Additionally, changing the filling material within the wall cavity is also an option. Selecting materials with lower thermal conductivity can reduce the overall thermal transmission of the wall [28,29].

Exterior Insulation and Finish Systems (EIFS) are exterior wall cladding systems that utilize rigid insulation boards on the outer layer of the wall, with a gypsum-like appearance as the outer skin. The most common type of EIFS is polymer-based (PB) systems. This system involves applying a nominal 1/16-inch-thick reinforcing base coat layer on top of the insulation layer before applying the finish coat. The insulation material typically consists of

closed-cell expanded polystyrene (EPS), which can be adhered to or mechanically attached to the substrate [23,25,26,30,31]. Another less common type of EIFS is polymer-modified (PM) systems. This system involves applying a layer of reinforcing base coat with a nominal thickness of 3/16 inch to 1/2 inch on top of the insulation layer before applying the finish coat. The insulation material usually consists of extruded polystyrene foam (XPS) and is mechanically attached to the substrate and wall structure [25,27,30,31]. Additionally, mineral wool is also a commonly used new construction material [30,32].

Climate conditions require different insulation thicknesses to control heating and cooling energy consumption. In temperate regions, the standard thickness of exterior wall insulation materials ranges from 30 to 50 mm to achieve various energy-saving goals [33]. Increasing the insulation layer thickness to above 26 mm in hot summers and cold winter regions does not significantly improve the walls' thermal insulation and energy-saving effects [34]. Furthermore, measures can be taken to improve the coefficient of expansion, porosity, and sealing of residential buildings with wood-structure walls [29].

Detailed data are summarized in Table 3.

Table 3. Data summary of reviewed studies in the wall systems retrofit program. (Definition of building types in the table: According to China's Uniform Standard for Civil Building Design GB50352-2019, buildings with one to three floors are categorized as low-rise residential, four to six floors as mid-rise residential, seven to nine floors as mid-high-rise residential, and ten floors and above as high-rise residential. Explanation of retrofit measures in the table: The text outside parentheses indicates the original structure, while the text inside parentheses indicates the retrofit measures. Explanation of U-values before and after retrofit in the table: The text outside parentheses represents the U-value before retrofit, while the text inside parentheses represents the U-value after retrofit).

City and Region	Acreage (m^2)	Building Types	Retrofit Measures (Within Brackets)	Comparison of U-Value before and after Renovation (W/m^2K)	Energy Saving Rate	Reference
Tianjin (Cold zone)	2711.75	mid-rise	360 mm solid clay brick, (65 mm EPS expanded polystyrene)	1.565 (0.439)	-	[23]
	4333.93	mid-rise	360 mm solid clay brick, (60 mm EPS expanded polystyrene), 30 mm insulation mortar	1.295 (0.442)	-	[23]
	17,146.07	high-rise	200 mm concrete reinforced, (75 mm EPS expanded polystyrene)	0.642 (0.458)	-	[23]
Nanjing (1980) (hot summer and cold winter)	7368.00	low-rise	(20 mm XPS extruded polystyrene)	3.375	36.9%	[25]
Nanjing (1985) (hot summer and cold winter)	7777.33	mid-rise	(20 mm XPS extruded polystyrene)	3.147	41.7%	[25]
Nanjing (1990) (hot summer and cold winter)	20,525.00	mid-rise	(20 mm XPS extruded polystyrene)	2.738	34.4%	[25]
Nanjing (1995) (hot summer and cold winter)	26,598.00	mid-rise	(20 mm XPS extruded polystyrene)	2.071	22.5%	[25]
Beijing (Cold zone)	-	mid-rise	80 mm EPS polystyrene board)	1.67	34.7%	[26]
Beijing (Cold zone)	2693.00	mid-rise	40 mm cement mortar, 240 mm clay brick, (120 mm EPS)	2.080	40.0–50.0%	[27]

Table 3. *Cont.*

City and Region	Acreage (m^2)	Building Types	Retrofit Measures (Within Brackets)	Comparison of U-Value before and after Renovation (W/m^2K)	Energy Saving Rate	Reference
Jining, Shandong Province (Cold zone)	11,142.00	high-rise	50 mm Concrete/mortar/mortar cement screed, (36 mm Vacuum insulation plate), 45 mm XPS-CO2 blowing, 20 mm Concrete/Gypsum/ mortar—Cement mortar, 200 mm Reinforced concrete	0.62 (0.148)		[28]
Qingdao, Shandong Province (Cold zone)	1825.40	low-rise	Brick timber framed (Insulation walls)	1.200 (0.300)	-	[29]
Tongren, Guizhou province (hot summer and cold winter)	-	low-rise	Wood walls, Masonry walls, Ceiling, Wood floor, Windows, Doors, (210 mm XPS extruded polystyrene, drywall)	-	56.0%	[30]
Jining, Shandong Province (Cold zone)	126.20	low-rise	(80 mm EPS panel)	0.273	-	[31]
			(120 mm EPS panel)	0.241		
			25 mm Vacuum insulation board	0.258		
			(115 mm Rock wool board)	0.276		
			(130 mm Rock wool board)	0.265		
			(65 mm XPS panel)	0.343		
			(90 mm XPS panel)	0.237		
Huilong, Hunan Province (hot summer and cold winter)	-	mid-rise	5 mm putty paint, 10 mm cement mortar, 180 mm clay brick, 10 mm cement mortar, 10 mm outside porcelain tiles, (250 mm rock wool insulation)	2.320 (0.125)	48.0%	[32]

- Window and shading system retrofit program

The alternatives for window replacements in residential building renovations encompass a variety of traditional and advanced window systems with varying thermal performance [35]. The overall thermal performance of windows is a function of the glass, the frame, and the surrounding details. Typically, the overarching objective is to achieve optimal daylight transmission at minimal heat transfer costs.

Aluminum frames are the most widely used window frame material, while wood, vinyl, and fiberglass are relatively common in the residential market, offering better energy performance compared to aluminum.

When it comes to selecting window glass, Double or triple-pane reflective glass typically offers higher insulation performance than single-pane reflective glass [36]. However, single-pane reflective glass can significantly reduce solar heat gain and may be the optimal window glass choice for relatively warm climate regions. Double-pane reflective glass is also increasingly utilized in cooling-dominated regions. In regions characterized by

hot summers and cold winters or cooling dominance, for energy-saving requirements, exterior windows are still recommended to use 6/12 mm double-glazed glass and 6/12 mm low-emissivity (Low-E) glass [37]. The 6 mm single-pane Low-E glass exhibits better thermal properties than ordinary glass of equivalent thickness and is suitable for reducing building energy consumption in relatively warm regions [38]. Given recent trends in China, five main types of window glass are predominantly used: 6 mm single-pane Low-E glass, 6/9 mm airtight double-glazed glass, 6/12 mm airtight double-glazed glass, 6/12 mm double-glazed Low-E glass, and 6/15/6 mm airtight triple-glazed glass. Their thermal performance for building renovations is determined in the DesignBuilder tool (Table 4).

Table 4. Alternative window retrofit measures in various climates.

Type of Glass	U-Value (W/m^2K)	Emissivity	SHGC	Emissivity
6 mm single clear low-e	4.85	0.84	0.30	0.10
6/9 mm double clear with air-sealed	3.26	0.84	0.70	0.60
6/12 mm double clear with air-sealed	2.67	0.84	0.70	0.60
6/12 mm double clear low-e with air-sealed	1.76	0.84	0.57	0.47
6/15/6 mm triple clear with air-sealed	1.69	0.84	0.61	0.47

Installing adjustable angle sun shading devices on building facades or windows allows for the adjustment of the shading panel's tilt angle based on the sun's height and angle, achieving optimal shading effects. The appropriate projection of the cantilever is approximately 850 mm [39]. Additionally, interior sun shading curtains or blinds can be installed to control indoor lighting and heat input by adjusting the opening degree of the curtains or blinds according to needs [40,41]. Research has shown that external shading devices are more effective in reducing solar heat gain compared to internal shading devices, as they do not cause overheating in the summer due to heat retention [40]. Furthermore, optimization of shading systems installation is required based on the building's climate zone and specific orientation [28,42].

- Roof system retrofit program

Roof renovation is crucial for reducing energy consumption and enhancing overall building performance, particularly in highly urbanized areas [43]. In roof renovation, insulation materials need to be installed considering the requirements of the roof structure [44], such as extruded polystyrene (XPS) [23,28], expanded polystyrene (EPS) [26], rock wool [31,32,45], and vacuum insulation panels [28]. Retrofitting the structural roof deck can meet the requirements of sustainable renovation, such as converting to a pitched roof to improve insulation and waterproofing performance [31]. International Building Code (IBC) and International Existing Building Code (IEBC) aim to guide the maintenance and repair of structural roof decks. However, leaky roofs can reduce the lifecycle performance of roofs, so special attention needs to be paid to the airtightness of roof components, and consideration can be given to replacing roof covering materials, such as rubber EPDM roof membranes. It can adhere chemically to insulation materials or substrates, forming a protective layer to prevent roof system failures [46]. Additionally, integrated photovoltaic (PV) solar panels can be installed on the roof to generate electricity from solar energy, enhancing energy efficiency and reducing dependence on traditional energy sources [31]. Furthermore, planting vegetation on the roof to create a green roof can provide cooling, insulation, and air purification effects [23]. Detailed data are summarized in Table 5.

Table 5. Data summary of reviewed studies in the roof system retrofit program. (Definition of building types in the table: According to China's Uniform Standard for Civil Building Design GB50352-2019, buildings with one to three floors are categorized as low-rise residential, four to six floors as mid-rise residential, seven to nine floors as mid-high-rise residential, and ten floors and above as high-rise residential. Explanation of retrofit measures in the table: The text outside parentheses indicates the original structure, while the text inside parentheses indicates the retrofit measures. Explanation of U-values before and after retrofit in the table: The text outside parentheses represents the U-value before retrofit, while the text inside parentheses represents the U-value after retrofit).

City and Region	Acreage (m^2)	Building Types	Retrofit Measures (Within Brackets)	Comparison of U-Value before and after Renovation (W/m^2K)	Energy Saving Rate	Reference
Tianjin (Cold zone)	2711.75	mid-rise	120 mm, Reinforced concrete, (30 mm fly ash ceramic replaced by 120 mm XPS extruded polystyrene)	2.634 (0.265)	-	[23]
	4333.93	mid-rise	120 mm Concrete (reinforced), (120 mm XPS extruded polystyrene), (60 mm Green eco-roofing material)	0.661 (0.248)	-	[23]
	17,146.07	high-rise	120 mm Reinforced concrete, (130 mm XPS extruded polystyrene)	0.588 (0.247)	-	[23]
Beijing (Cold zone)	-	mid-rise	130 mm Cement mortal, 100 mm Concrete cement mortal, Cement-expanded perlite, (Add 80 mm EPS)	1.366	7.0%	[26]
Jining, Shandong Province (Cold zone)	11,142.00	high-rise	45 mm Concrete/mortar/mortar cement screed, (32 mm Vacuum insulation plate), 60 mm XPS-CO_2 blowing, 20 mm Concrete/Gypsum/ mortar—Cement mortar, 100 mm Reinforced concrete	0.473 (0.150)	-	[28]
Qingdao, Shandong Province (Cold zone)	1825.40	low-rise	(Renewed tiles)	3.100 (0.260)	-	[29]
Jining, Shandong Province (Cold zone)	126.20	low-rise	(5.9 kWp rooftop photovoltaic system), (70–80 mm Rock wool board), (Pitched roof)	-	20.5%	[31]
Huilong, Hunan Province (hot summer and cold winter)	-	mid-rise	50 mm cement, 100 m reinforced concrete raft, 400 mm air gap, 10 mm wood board, 5 mm putty paint (250 mm rock wool insulation)	1.760 (0.123)	48.0%	[32]

- Lighting and Control System Retrofit Program

In addition to impacting the physical and mental well-being of building occupants, the internal lighting system of a building is both the primary consumer of electrical energy and the main source of internal heat. Light-Emitting Diodes (LEDs), as one of the most energy-efficient and rapidly developing lighting technologies, offer high-quality LED bulbs that not only have a longer and more durable lifespan but also provide light quality comparable to or even superior to other lighting methods [22]. Compact Fluorescent Lamps (CFLs), on the other hand, are commonly used as simple replacements for incandescent bulbs due to their significantly longer lifespan and higher energy efficiency. Therefore, retrofitting existing lighting systems with more energy-efficient lighting systems such as CFLs and LEDs presents significant development prospects. Here, both options are utilized to assess their impact on the building's energy performance, as shown in Table 6.

Table 6. Alternative lighting systems in various climates [47].

Type of Lighting	Energy Efficiency	Lifespan (hours)
Compact fluorescent lamps	36 W/lx	8000
LED lamps	4 W/lx	50,000

Furthermore, electronic ballasts can replace traditional magnetic ballasts to enhance the efficiency of lighting systems [47]. Additionally, the implementation of intelligent control systems, such as automatic light sensors and timers, is recommended to automatically adjust the switching of lighting fixtures based on requirements [48]. The purpose of these retrofit measures is to reduce energy consumption, lower operational costs, and improve indoor environmental quality.

- Heating, Ventilation and Air Conditioning (HVAC) and other building equipment systems retrofit program

In northern regions of China (covering some Cold and Severe Cold regions), residential neighborhoods commonly utilize district heating systems, with the vertical single-pipe system being a prevalent heating method [26]. Typically supplied by boiler rooms or thermal power plants, Ground-Source Heat Pumps (GCHP) systems offer the lowest energy consumption. This system involves the installation of heating pipes beneath the floor to heat indoor air while reducing the spread of dust and allergens caused by air convection [24,49]. Another popular renewable technology is solar domestic hot water systems, which distribute hot water through pipelines and provide heating via the floor; however, they operate effectively only in climates with minimal icing, typically in regions with hot summers and cold winters [24]. Traditional coal-fired furnaces can be replaced with clean heating equipment such as high-efficiency boilers, heat exchangers, natural gas heaters, electric heaters, and air-source heat pumps [50,51]. Intelligent temperature control systems can be installed, adjusting heating equipment operation automatically based on indoor temperature and demand to enhance energy utilization efficiency, albeit at a higher cost [47].

Additionally, field measurements conducted on 38 heating stations revealed that pipe overheating and heat loss are the primary reasons for the difference between actual and theoretical heat consumption [52]. Consequently, researchers have developed a novel simulation model for centralized heating systems in residential neighborhoods to predict the energy performance of buildings connected to the system over time, aiding managers in real-time energy monitoring [53]. Demand-side optimization of residential heating systems also warrants consideration [54].

For indoor and outdoor ventilation, it is recommended to utilize efficient ventilation equipment such as adjustable ventilation fans [50]. Additionally, the installation of new ventilation control systems like Mechanical Ventilation with Heat Recovery (MVHR) [28,32]

and Dedicated Outdoor Air Systems (DOAS) [55] can be considered. By incorporating heat recovery devices, MVHR systems recover heat from indoor exhaust air, utilize damaging pressure infiltration to obtain fresh air, and preheat it, reducing heating demand and improving indoor air quality [32].

In southern regions of China (covering some Hot Summer and Cold Winter, Hot Summer and Warm Winter and Temperate regions), except for areas with a heating consumption pattern characteristic of some regions with hot summers and cold winters [56], residential neighborhoods typically lack district heating systems. Families often rely on standalone air conditioning units to maintain indoor comfort during winter. The most popular air conditioning units in residential buildings are split-type air conditioners with cooling capacities below 4500 W [57,58]. Split-type air conditioners are mainly categorized into fixed-frequency (constant-speed) and variable-frequency (inverter) types. Fixed-frequency air conditioners, known for their longevity, were prevalent in China until the mid-2000s. In recent years, there has been a rapid development of fully DC inverter air conditioners that are much more energy efficient than previous systems, with energy efficiencies for such air conditioners typically above 4.5 and possibly as high as 8.5 [59]. However, due to the relatively high cost of replacing air conditioners, they often yield negative economic benefits. Therefore, setting the target temperature for air conditioning to 26 °C/20 °C is the most cost-effective retrofit measure with significant energy-saving impacts. This only requires residents to improve their energy usage habits and represents a cost-free reform measure with evident benefits [25]. Moreover, installing intelligent air conditioning control systems that automatically adjust the operation of air conditioning equipment based on indoor temperature and demand is another viable approach [47]. Detailed data are summarized in Table 7.

Table 7. Data summary of reviewed studies in the HVAC and other building equipment systems retrofit program.

City and Region	Acreage (m^2)	Building Types	Material	Retrofit Measures	Energy Saving Rate	Other Evaluations	Reference
-	307.12	mid-rise	Radiator Heating, Boiler HW, Natural Ventilation (Fuel 5 Coal) + Packaged Terminal Air Conditioner (PTAC)	Fancoil Unit (4-Pipe) Air Cooled Chiller	18.9%	-	[24]
				Solar-assisted Heated Floor + PTAC	23.4%		
				GSHP Water to Water HP, Heated Floor + PTAC	36.7%		
				Heated Floor, Boiler HW, Natural Ventilation + PTAC	7.9%		
Nanjing (1980) (hot summer and cold winter)	7368.00	low-rise	-	Set the target temperature to 26 °C in summer and 20 °C in winter, Increase COP of air conditioner to 3.3	23.0%	-	[25]
Nanjing (1985) (hot summer and cold winter)	7777.33	mid-rise			19.9%		
Nanjing (1990) (hot summer and cold winter)	20,525.00	mid-rise			22.7%		
Nanjing (1995) (hot summer and cold winter)	26,598.00	mid-rise			32.3%		

Table 7. *Cont.*

City and Region	Acreage (m^2)	Building Types	Material	Retrofit Measures	Energy Saving Rate	Other Evaluations	Reference
Beijing (Cold zone)	-	mid-rise	Pipe system: vertical single pipe system	Install a cross-nozzle between the inlet and outlet of each radiator, Install an automatic thermostatic valve and a heat distribution meter on each radiator, Set the indoor temperature to 16 °C	19.0%	-	[26]
			Thermostatic valve: The valve is available, but cannot be put into use				
			Heat meter: Household heat measurement cannot be carried out without heat meter				
Jining, Shandong Province (Cold zone)	11,142.00	high-rise	Traditional district heating, radiators and individual air conditioning for cooling only	Mechanical Ventilation Heat Recovery (MVHR)		75% of heat recovery	[28]
Huilong, Hunan Province (hot summer and cold winter)	-	mid-rise	-	mechanical ventilation system with heat recovery (MVHR) function		80% of heat recovery	[32]
Changning District, Shanghai (hot summer and cold winter)	191.30 (Suite)	mid-rise	Underfloor heating system	Water piping underfloor system (Boiler), Upper air supply Ventilation, VRV (Indoor device)	-	The indoor terminal can be noisy during summers.	[49]
				Water piping underfloor system (Boiler), Upper air supply Ventilation, CER (Capillary radiation mat)	-	The most comfortable system	
Tangshan (Cold zone)	-	-	-	Vertical two-pipe system	56.3%	-	[50]
				Household circulation horizontal parallel double pipe system	51.8%		
				Vertical single pipe cross pipe system	58.6%		
Tianjin (Cold zone)	-	-	-	The new heat exchange station takes indoor pipe network hot water as the primary water side and building variable flow heating water as the secondary water side	43.4–50.3%	-	
				High energy efficiency boiler			
Tianjin (Cold zone)	5700.00	-	-	Dedicated outdoor air system (DOAS)	-	Meet the indoor fresh air requirements	[55]
-	-	-	Split room air conditioner 4500 W < cooling capacity < 7100 W	Fixed-frequency (existing one)	-	Energy efficiency: 2.5	[57,58]
				Inverter		Energy efficiency: 3.5	
				Full DC inverter		Energy efficiency: 4.5	

3.2.2. Building Performance Simulation (BPS)

The simulation stage quantitatively validates the assessment findings, with building modeling techniques forming an integral part of the computer-aided design phase [60]. Building Performance Simulation (BPS) is commonly employed in the sustainable assessment of existing residential buildings in China. This involves modeling the building and simulating various parameters such as temperature, humidity, and airflow during different seasons through simulation programs. By comparing the simulation results with actual measurement data, the number of experimental scenarios is reduced, and the accuracy of the retrofit models is validated. This optimization of design and operation before practical implementation helps reduce empirical errors and construction costs [61]. Additionally, BPS plays an increasingly crucial role in developing low-energy, high-performance buildings and achieving goals of reducing energy consumption and greenhouse gas emissions in the construction industry [62], a role that extends to sustainable retrofitting of existing residential buildings in China.

Building Performance Simulation (BPS) is now widely and successfully used in the retrofitting of existing residential buildings in the following areas:

- Simulating energy-efficient retrofit measures for existing residential building envelopes [24,29,30,32,35,45,63–68];
- Optimizing management, operation, and control of existing residential building HVAC (heating, ventilation, and air conditioning) and other building equipment systems [23–26,28–30,32,35,36,40,42,47,49,51,54,55,65,67–78].

As illustrated in Figure 8, building performance simulation (BPS) is more frequently utilized in optimizing building equipment systems, making it more popular compared to envelope energy efficiency retrofits from this perspective. Overall, BPS is increasingly employed at all stages of the building life cycle, encompassing the analysis and prediction of building energy consumption, measurement and verification, carbon footprint assessment, energy efficiency measures, and cost analysis. With the rapid advancement of global energy-saving and carbon reduction efforts, Building Energy Modeling and Simulation (BEMP) will play a more crucial and fundamental role in the building sector, supporting future policy formulation and development planning [79].



Figure 8. The number of times BEMP were used in the reviewed literature.

It is important to note that because BEMPs are based on simplifications of reality, they may only sometimes precisely reflect reality or may even differ significantly from it [80]. However, they are responses generated by predefined randomized algorithms, and therefore, to some extent, they still offer significant advantages [81].

To tackle the fundamental challenges of building performance analysis, building simulation tools have undergone rapid development worldwide since the 1960s [62]. As depicted in Figure 9, this paper summarizes the simulation tools utilized in the literature reviewed. In general, these tools can be categorized into three main groups:

- Stand-alone simulation program

These programs feature independent simulation kernels, enabling them to run autonomously without calling other programs. Some tools utilize graphical user interfaces (GUIs), such as DeST, while others employ general scripting languages and a set

of programming functionalities and libraries, like EnergyPlus. Programs such as TRNSYS [51,53,54,66] and DOE-2 [75] are primarily used for simulating HVAC system control processes. In contrast, PKPM, which uses DOE-2 as its computational kernel, can calculate carbon emissions during building materials production, transportation, and construction stages [82]. HelioScope and Integrated Environmental Solutions Virtual Environment (IES-VE) are used to calculate available roof areas and assess the performance of solar photovoltaic systems [46]. They employ simplified room/zone thermal mass balance models and use accurate yet complex system models to depict the rapid dynamic response of each component under various control strategies. Another group, including EnergyPlus [25,28,31,35,36,44,64,67,68,70,72,76,83–86], DeST [73,77], WUFI® Plus [30], and IDA-ICE [74], focuses primarily on the long-term dynamic thermal performance of buildings and systems. Therefore, they utilize comprehensive room/zone models and simplified system models, making them more suitable for simulating the annual energy consumption of buildings. Additionally, Ecotect Analysis is a comprehensive computer simulation analysis software used for analyzing various aspects of the building environment, such as thermal, lighting, and acoustic environments, as well as economic and cost analysis, meteorological data, etc., and it is widely used [23,29,72,87].

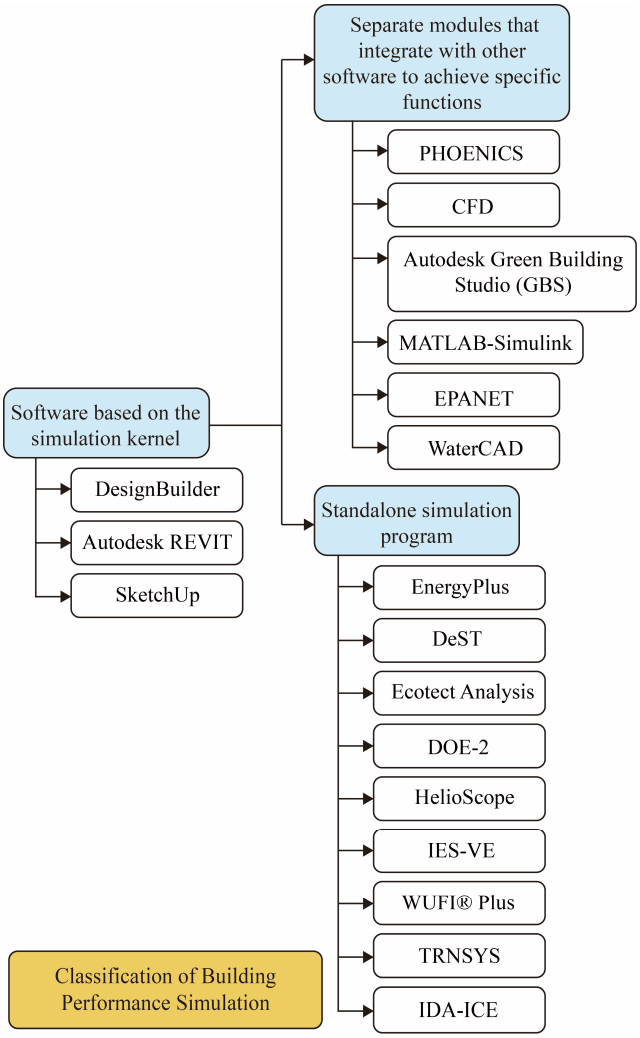


Figure 9. Classification of BPS.

- Emulation kernel-based software

Such software requires the invocation of independent simulation kernels to build performance simulations. However, they possess user-friendly features, making them

convenient and suitable for architects and engineers in the building industry. DesignBuilder is widely recognized as the most popular simulation software [23,26,28,31,32,42,44,45,53,65,68,76,83,88]. Additionally, Autodesk REVIT [42,87,89–91] and SketchUp [67,72,86], as Building Information Modeling (BIM) software, are also commonly used. These programs support users in constructing building models more straightforwardly and then converting them into dedicated models for respective simulation kernels for conducting building performance simulation and result analysis.

- Individual modules that integrate with other software to fulfill specific functions

In recent years, the construction industry has increasingly adopted new materials and technologies to reduce energy consumption, such as double-layered exterior walls [40], phase-change walls [40], and passive radiant cooling [23,28,31,32,36,40,41,44,51,63,66,78,85,91]. These advancements necessitate more accurate and specialized modules to achieve joint simulation between building energy simulation programs (BESP) and different modules. Furthermore, as an understanding of building performance simulation deepens, numerous researchers have developed various modules related to climate, occupant behavior, building envelope structures, and HVAC equipment. For instance, Computational Fluid Dynamics (CFD) is a computer-aided engineering (CAE) tool used to simulate fluid flow under various engineering models, often applied to natural ventilation and airflow in buildings [23,70]. PHOENICS is also used to simulate climate systems and wind environments [23]. Additionally, Autodesk Green Building Studio (GBS), as a plugin for REVIT, is used to determine climate data and estimate the annual energy consumption of buildings [87], while EPANET and WaterCAD are used for hydromechanical simulation [53].

Figure 10 shows the frequency of using each type of BPS in the reviewed literature.

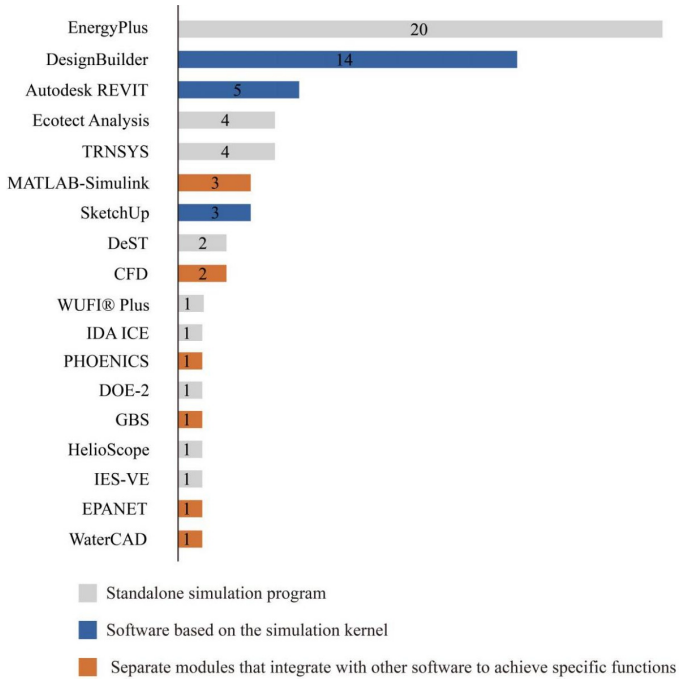


Figure 10. The number of times BPS was used in the reviewed literature.

3.2.3. Appropriateness Assessment

To meet the growing demand for putting sustainable concepts into practice, various systems have been developed and widely utilized to assess the environmental performance of buildings. Sustainability assessment systems represent a range of tools used to measure the impacts of buildings at every stage, from design to occupancy, with particular emphasis on the construction phase and encompassing aspects from resource consumption to user well-being. Therefore, the objectives of these assessment systems are to ensure sustainability

throughout the entire lifecycle of buildings, including design, construction, operation, maintenance, and demolition/deconstruction stages, in pursuit of interrelated parameters such as environmental, social, economic, and functional aspects.

According to surveys conducted by the International Energy Agency (IEA), there are over 100 international methods, frameworks, and tools related to green building assessment systems. The current assessment systems considered most relevant in this field are Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) [92]. This is because they are widely applied and have continuously evolved over many years to update dynamically according to market or demand needs. The Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) is also used to assess historic residential buildings [93].

- LEED

LEED (Leadership in Energy and Environmental Design) is developed by the U.S. Green Building Council (USGBC) to measure the performance of buildings or building groups according to predetermined standards. Its development aims to adapt to the needs of various types of buildings throughout their lifecycle, including from construction (regardless of geographical location) to the usage stage. LEED projects are evaluated based on earning points in nine sustainable development issue areas: integrative processes, location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation, and regional priority. Depending on the points earned, projects are classified into one of four levels (in ascending order): Certified, Silver, Gold, or Platinum. This system is considered the most widely applied system in China and globally [92].

- BREEAM

BREEAM (Building Research Establishment Environmental Assessment Methodology), established by Building Research Establishment (BRE) in 1990, is regarded as the "world's most widely used sustainability assessment method" for urban planning, infrastructure, and building projects. This method evaluates buildings based on performance benchmarks, followed by classification and certification according to sustainability grades, including Pass, Good, Very Good, Excellent, and Outstanding. All available tools assess the impact of construction on aspects such as energy, health and well-being, innovation, land use, materials, management, pollution, transportation, waste, and water through a series of parameters. This system is considered a more specific and architecture-focused tool for research topics [92].

- CASBEE

CASBEE (Comprehensive Assessment and System for Building Environmental Efficiency) is a comprehensive assessment system developed by the Japan Building Environmental and Energy Efficiency Center for evaluating the environmental performance of buildings. It aims to assess the sustainability and environmental friendliness of buildings. The assessment method of CASBEE is based on buildings' overall performance and environmental load. It includes multiple assessment indicators covering aspects such as indoor environmental quality, outdoor environmental quality, resource utilization, energy utilization, and material usage [93].

A comprehensive and multidimensional assessment framework must be developed for the sustainable renovation of existing residential buildings in China. This framework should consider economic benefits, environmental impacts, and human health effects. Adopting a multidisciplinary perspective can provide a more scientific basis for environmentally adaptive renovations. However, it is vital to acknowledge the potential conflicts between economic and environmental goals and strive to achieve the optimal balance between economic and environmental benefits.

As depicted in Figure 11, this study summarizes the suitability assessment methods adopted in the reviewed literature. Generally, these methods can be categorized into three

main types. Figure 12 provides a quantitative analysis of these three categories of methods identified in the reviewed literature:

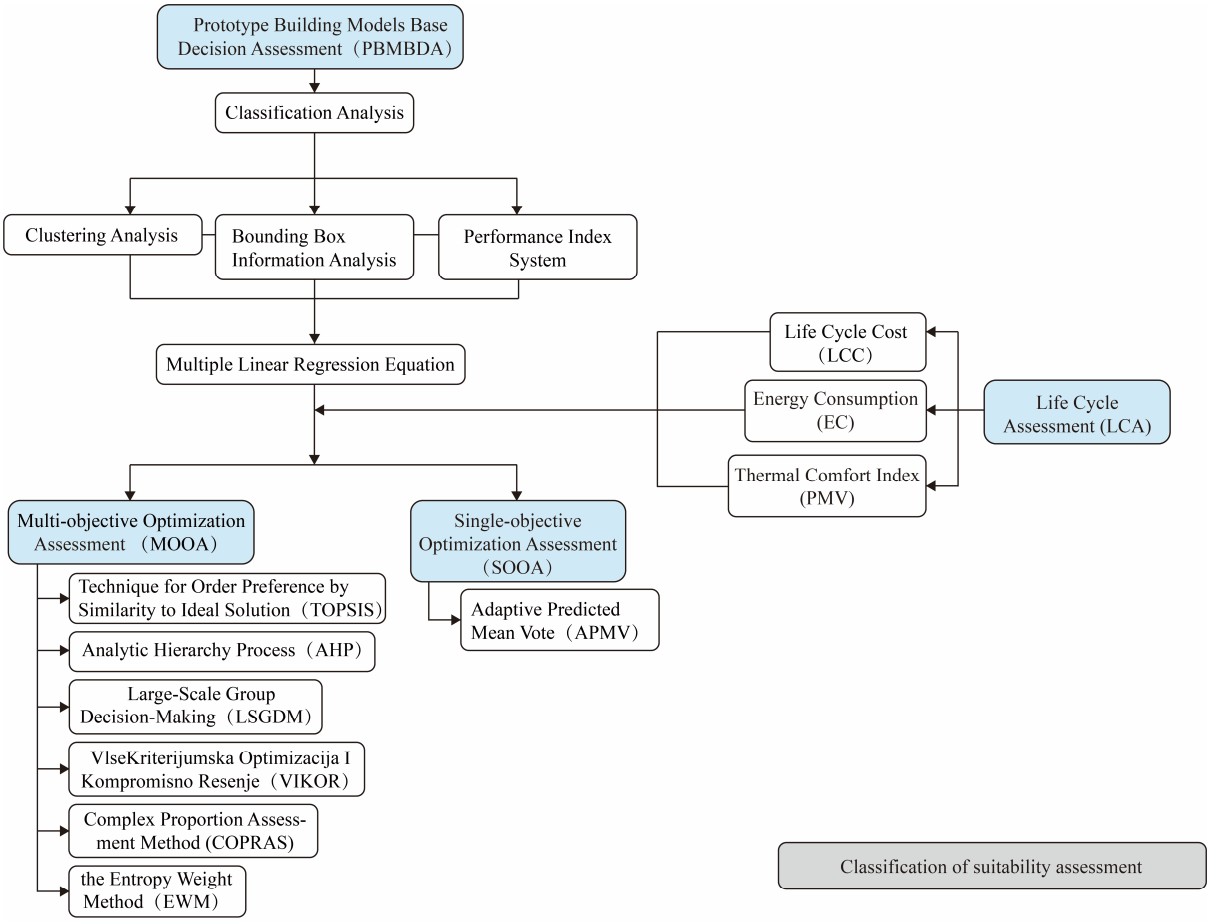


Figure 11. Classification of suitability assessment.

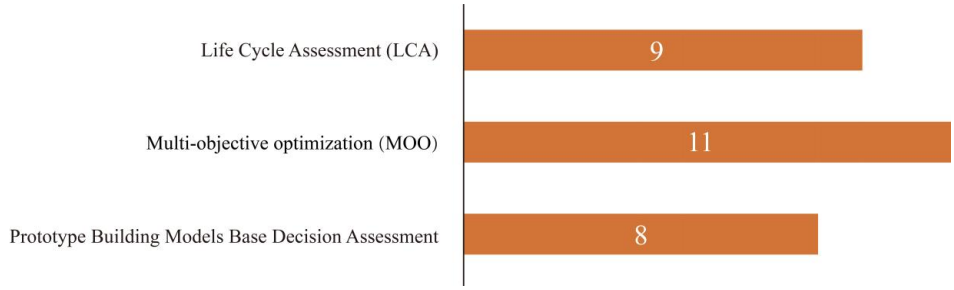


Figure 12. The number of times evaluations were used in the reviewed literature.

- Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a standardized method to quantitatively assess the environmental impacts of different solutions and alternative scenarios [94]. The primary advantage of LCA lies in its consideration of the entire life cycle of alternatives, covering processes from raw material production, manufacturing, and use phase to final disposal and waste treatment. While LCA tools such as SimaPro and GaBi are primarily applied to new construction, it is also necessary to apply them to existing buildings to evaluate impacts such as renovation or refurbishment [95] and explore the effects of building renovation on environmental sustainability [96]. Currently, BIM integration is often used to streamline the LCA process to improve efficiency and accuracy, as illustrated in Figure 13.

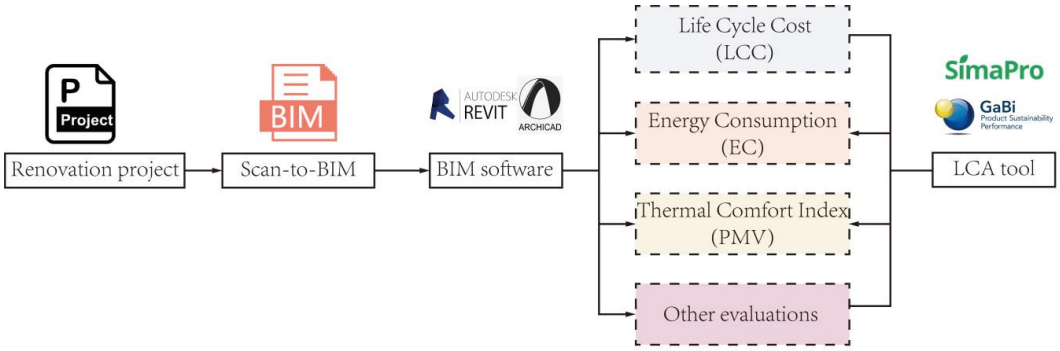


Figure 13. BIM process integrated with LCA approach framework.

Researchers have combined the Scan-to-BIM (Building Information and Modeling) and Life Cycle Assessment (LCA) methods in the sustainable renovation of existing residential buildings in China. Using three-dimensional point clouds and parameterization algorithms, they generated BIM models with meager error rates, addressing issues in the information input stage. These models were then used to evaluate existing buildings' economic, environmental, and human health impacts [97]. Additionally, a method combining energy value analysis and LCA was employed to assess energy efficiency and environmental impacts of building envelope retrofitting [69]. Furthermore, specific to the thermal metering and energy efficiency retrofitting of existing residential buildings in China, researchers categorized, characterized, and quantified evaluation indicators based on LCA theory [98]. They applied a multi-index comprehensive evaluation method to process these indicators mathematically.

Moreover, BIM was utilized to predict the energy consumption (EC) and thermal comfort (PMV) of buildings. Corresponding target adaptability functions were established, and hybrid machine learning algorithms were combined to optimize the design parameters of building envelopes and HVAC systems to achieve goals of reduced energy consumption, lower life cycle costs, and improved thermal comfort [64]. Despite these advancements, a significant challenge in the renovation process of existing Chinese residential buildings still needs to be determined as the most cost-effective technological path for a specific project [99]. Hence, LCA is often employed to assess life cycle costs (LCC) [26,75,79,86], defined as the sum of all expenses related to energy transmission systems throughout the building's lifecycle, including energy use and renovation costs [100]. Additionally, LCC analysis can be combined with payback period analysis to determine the balance between the cost of renovation measures and energy savings [32].

- Multi-objective Optimization Assessment (MOOA)

Residential building energy retrofitting can be viewed as a multi-objective problem. Designers typically need to evaluate multiple solutions and conduct multiple dynamic thermal simulations to determine the optimal building configuration that minimizes energy consumption. The optimization of building retrofits involves identifying interventions (i.e., retrofits) in the building envelope, HVAC systems, and potentially energy production facilities during the retrofit phase. The objective is to minimize the target function.

In a substantial body of research on building optimization, the objective function typically involves multiple variables such as energy consumption, economic factors, and environmental considerations. Recent studies have systematically evaluated the economic aspects using Net Present Value (NPV) analysis [48,90]. These studies assume a 20-year lifecycle for building retrofit measures and use a discount rate of 3% based on data from the FRED Economic Research website for NPV analysis. Researchers have proposed an optimization method for decision-making on existing building retrofit strategies based on NPV, aiming to determine energy-efficient and cost-effective retrofit alternatives by comparing the overall benefits of various retrofit solutions. These methods also establish target weights and priorities for energy improvement measures within a multi-criteria

problem framework. They have developed a comprehensive optimization framework for energy efficiency and cost-effectiveness and have concluded that:

(1) In cold regions of China, achieving a 60% energy savings can result in the highest optimal Net Present Value (NPV) [90].
(2) In severely cold regions of China, the optimal energy savings target may be 50%, as both 60% and 50% energy savings yield the same maximum Net Present Value (NPV) [90].
(3) In the hot-summer and cold-winter regions of China, the maximum benefit in terms of Net Present Value (NPV) can be achieved by targeting 40% energy savings [48].
(4) According to the JGJ75-2012 "Energy Efficiency Design Standard for Residential Buildings in Hot Summer and Warm Winter Zones", energy savings of up to 50% can be achieved [101].
(5) In temperate regions of China, the maximum benefit in terms of Net Present Value (NPV) can be achieved by targeting 30% energy savings [48].

These metrics provide optimal solutions for energy retrofitting of existing residential buildings in China, offering a standardized and replicable assessment model for retrofit evaluations (see specific details in the conclusion).

Finding unique solutions for multi-objective optimization typically involves optimization and decision-making. Hybrid machine learning algorithms (such as random forests, NSGA-II, and NSGA-III intelligent algorithms) have performed well in multi-objective optimization. Therefore, they are suitable for multi-objective problems in the field of building performance optimization and are commonly used in the sustainable renovation of residential buildings in China [64,85,91]. The multi-objective optimization problem can be summarized as follows:

$$\begin{cases} \min/\max f_m(x), m = 1, 2, \ldots, M \\ \text{subject to } g_j(x) \geq 0, j = 1, 2, \ldots, J \\ h_k(x) = 0, k = 1, 2, \ldots, K \\ x_i^L \leq x_i \leq x_i^U, i = 1, 2, \ldots, n \end{cases} \quad (1)$$

In this context, $f_m(x)$ represents the objective function of the problem. The multi-objective optimization problem consists of two objective functions ($m = 2$), namely energy savings and monetary costs, the latter encompassing investment and electricity charges. A set of x_1, x_2,..., x_n denotes a particular solution in an n-dimensional vector, representing various configurations of renovations, termed decision variables. $g(x)$ and $h(x)$ represent the inequality and equality constraints of a solution, respectively. x_i^L and x_i^U represent the lower and upper bounds of a variable x_i, respectively.

Researchers often utilize decision-making methods such as TOPSIS, VIKOR, AHP, COPRAS, and EWM to select the optimal solution from the optimized solution set.

TOPSIS, a commonly used multi-criteria decision-making method, ranks alternatives based on their proximity to the evaluation and ideal objectives. Initially, some objectives need to be positively processed, followed by data normalization, which allows for the identification of the optimal and worst values among multiple objectives. Subsequently, the distance between each non-dominated solution and the ideal and anti-ideal solutions is calculated separately. The comprehensive distance serves as the basis for assessing solution equality and enables the computation of TOPSIS scores [49,64,76,86,91].

The VIKOR method is a multi-criteria decision-making technique similar to the TOPSIS method, as it revolves around determining the positive ideal solution and the negative ideal solution. Subsequently, it compares the evaluation values of alternative solutions based on their distances from the ideal values. Like TOPSIS, VIKOR also requires initial positive processing and normalization. However, the VIKOR method evaluates the merits of solutions by maximizing group utility and minimizing individual regret, ultimately selecting the optimal solution [86].

Analytic Hierarchy Process (AHP) is a mathematical model used to evaluate the importance and weights of indicators. This method assesses and selects the most suitable architectural design strategies. Researchers first categorize the indicators into four levels: the goal level, the indicator level, and the criterion level. Then, by constructing judgment matrices, experts pairwise compare the indicators at each level to determine their relative importance. Based on the experts' evaluations, the weights of each indicator are calculated. Finally, through AHP calculation, the comprehensive weights of each indicator in the evaluation index system are obtained [49,64,74,76].

Complex Proportionality Assessment (COPRAS) is another way of multi-criteria decision analysis. Its core idea is to determine the relative performance of each solution under different criteria by comparing each solution with other solutions [76]. To avoid the influence of subjective factors, entropy weighting can be used to make the weight allocation of indicators more objective [102].

Additionally, Large-Scale Group Decision-Making (LSGDM) is also a decision-making method. However, establishing a consensus model based on the K-means consistency model is required to ensure that the consensus degree of LSGDM meets the requirements [89].

- Single-objective Optimization Assessment (SOOA)

In residential building renovation, the single-objective optimization problem typically exists as a stringent constraint to reduce the number of solution sets in multi-objective optimization. The Adaptive Predicted Mean Vote (APMV) is an assessment index widely used in building thermal and humidity environment research, and it is especially suitable for assessing indoor thermal comfort in naturally ventilated buildings [45,100]. Its calculation formula is as follows:

$$\mathrm{APMV} = \mathrm{PMV}/(1 + \lambda * \mathrm{PMV}),$$

where λ represents the adaptive coefficient, a parameter intricately linked to the thermal zoning and performance characteristics of the building.

Predicted Mean Vote (PMV) values obtained through thermal environment simulations are used to calculate the APMV. According to the assessment levels in Table 8, the thermal and humidity environment is categorized into levels I, II, and III, corresponding to "satisfactory", "basically satisfactory", and "unsatisfactory", respectively. Level II and above are acceptable, while level III is unacceptable.

Table 8. Thermal and humid environment assessment grade for non-artificial cold and heat sources. Table data source: Literature [103].

Grade	Evaluation Index
I	$-0.5 \leq \mathrm{APMV} \leq 0.5$
II	$-1 \leq \mathrm{APMV} < -0.5$ or $0.5 < \mathrm{APMV} \leq 1$
III	$\mathrm{APMV} < -1$ or $\mathrm{APMV} > 1$

- Prototype Building Models Base Decision Assessment (PBMBDA)

The prototype model library decision is an approach based on building typology and statistical analysis for comparative assessment. In the review process of sustainable renovation of existing residential buildings in China, this evaluation method typically divides the assessment based on China's five architectural climate zones and building thermal design divisions to determine local prototype models [71,88,104,105]. This process usually includes the following steps, as shown in Figure 14:

(1) Data Collection: Information is gathered from national standards, reports, and other literature related to building design, energy, etc. Previous survey data and available project information are also collected to identify uncertainty factors and conduct a

comparative analysis, which is used for developing energy models for each prototype [48,88,97].

(2) Selection of building prototype: The probability distribution of all uncertainty factors is propagated using the Monte Carlo simulation method, and uncertainty factors are quantified through standard statistical methods [48]. Detailed specifications of prototype building energy models are determined through Scan-to-BIM technology, clustering analysis, and boundary box (location) information analysis [97] or by establishing a Performance Indicator System (PIS) through correlation analysis to select prototype buildings for building performance simulation [104].

(3) Validation: The accuracy of prototype building models is validated through comparison with measured data, and multiple linear regression equations are established for calibration [106].

(4) Model base decision: After constructing the prototype model library, economic and energy efficiency assessments for building energy retrofitting are conducted. At this stage, multi-objective decision optimization assessment is often combined. An optimization model is established based on objective functions, decision variables, and constraints to evaluate energy savings and economic feasibility in building renovation [88,90,105].

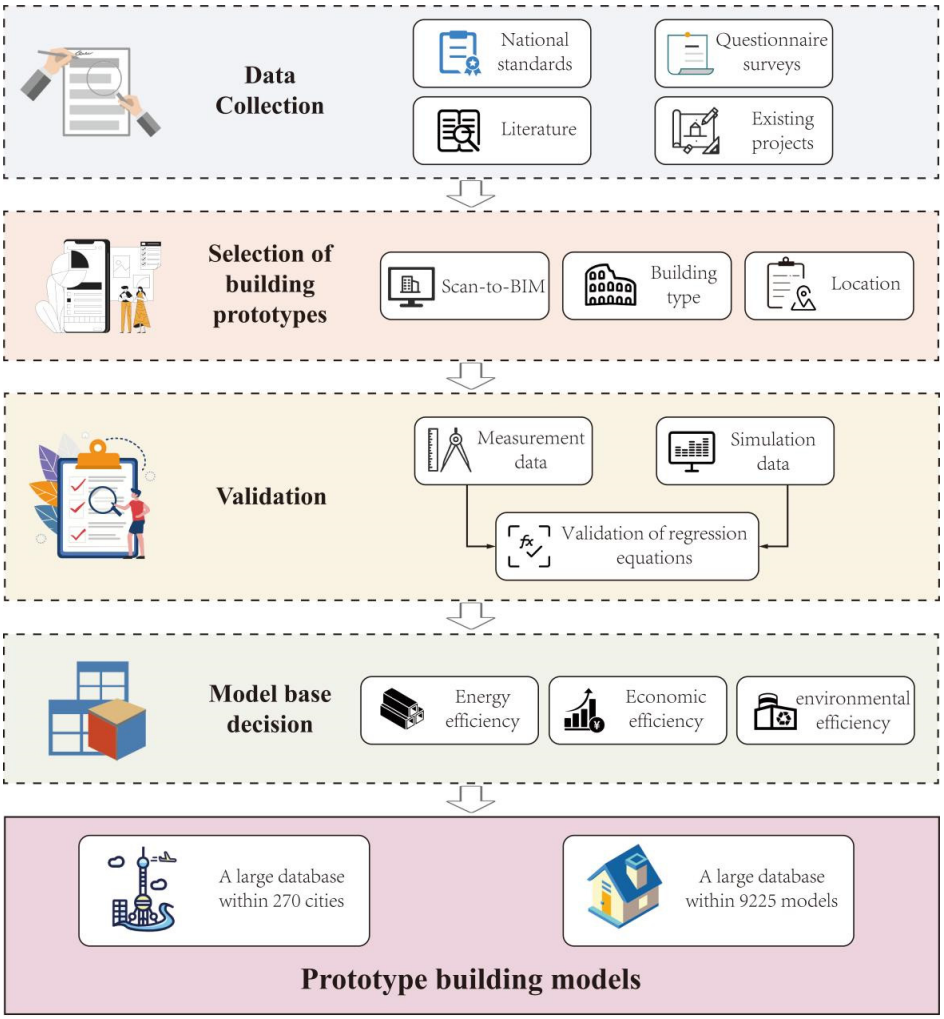


Figure 14. Schematic of overall technical approach.

Currently, prototype-building models have been applied in 270 cities across five climate regions, establishing an extensive database containing 9225 models. This facilitates users in conducting building energy simulations in different cities [71].

3.3. Influencing Factors and Solutions of Residents' Behavior

From the perspective of the leaders driving the renovations, the existing renovation of residential buildings in China is primarily led by the government and spontaneous initiatives from residents. Government-led renovations mainly focus on urban areas and can be categorized into central government-led and local government-led models [107]. Spontaneous renovations typically occur in rural areas across the country.

3.3.1. Statistical Analysis Based on Influencing Factors

Through relevant online and offline surveys and using the PESTEL model for goal orientation [108], the willingness and attitudes of homeowners in northern China towards government-led energy efficiency renovations were studied. Statistical analysis was applied to identify which combination of individual factors and barriers are most likely to have a negative impact on the likelihood:

(1) Correlation analysis: Examining the relationship between residents' attitudes and actual behavior [109].
(2) Independent samples *t*-test: Comparing the differences in actual behavior between groups with different attitudes [109].
(3) Chi-square test: Comparing the distribution of actual behavior among groups with different attitudes for significant differences [109].
(4) Structural equation modeling (SEM): Comparing differences between eastern and western China as well as different groups (education level, income level, age, and occupation) [110,111].
(5) Probit regression analysis: Identifying factors influencing residents' attitudes [109].
(6) These statistical analysis methods determined key factors influencing homeowners' decisions, including age, gender, education level, and building type. Essential barriers were identified, such as economic costs, imbalanced financial planning, spontaneous renovations, and loss of autonomy [112,113].

3.3.2. Strategy Advice Based on Stakeholders

To overcome the financing difficulties in the energy efficiency renovation of existing residential buildings in China, three key stakeholders, namely the government, energy service companies, and residents, were selected for study [114]. By improving the cost–benefit analysis method [115], different financing models were proposed, including the local government-led, property company-led, energy service, and heating supply company-led models. It was emphasized that with its responsibilities and tasks in energy efficiency renovation, the government should bear most of the costs through measures supported by fiscal and tax policies. These measures include increasing central government transfers, providing financial support, and optimizing tax policies [116–119]. Additionally, the current heating management system can be changed, with heat supply companies responsible for power generation, peak shaving, and primary network management. In contrast, several heating service companies are responsible for secondary network and terminal service management to address resident participation issues arising from management [120]. This model can serve as a reliable decision-making tool to improve the renovation of old residential buildings in China [116].

4. Conclusions

The current research framework in the realm of sustainable retrofitting for residential buildings in China still needs to be improved, with significant variations in building characteristics, economic conditions, and climatic factors across different thermal zones. To address this gap, this study systematically reviewed existing literature and summarized the research frameworks discussed in the literature review, as illustrated in Figure 15. Furthermore, building upon this framework, a retrofitting framework based on specific microclimate models for each thermal zone was developed for sustainable refurbishment.

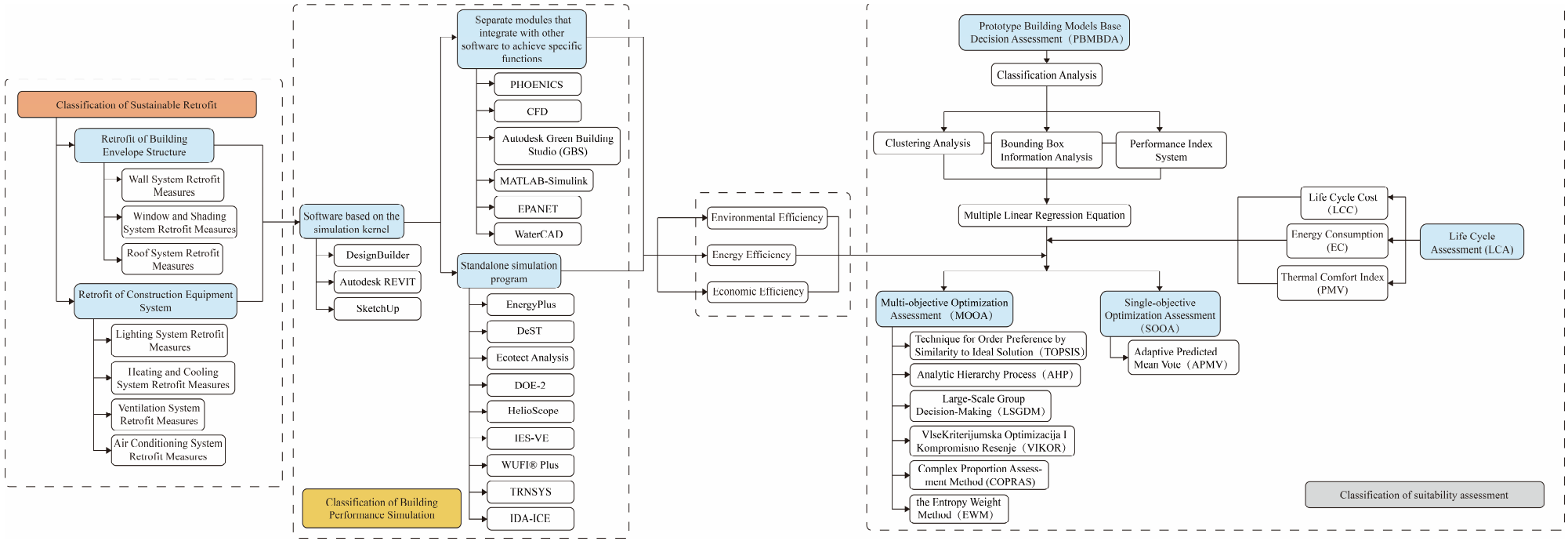


Figure 15. Summarize the research framework involved in the review literature.

Table 9 demonstrates the recommended retrofit measures based on the five primary thermodynamic zones.

Table 9. The recommended retrofit measures based on the five primary thermodynamic zones.

Building Systems	Cold Zone	Severe Cold Zone	Hot-Summer and Cold-Winter Zone	Hot-Summer and Warm-Winter Zone	Temperate Zone
Wall system	EPS, XPS, Rock wool board, Vacuum insulation plate (The thickness of the insulation layer can be referred to Figure 16)				
Window and shading system	6/12 mm double-glazed Low-E glass and 6/15/6 mm airtight triple-glazed glass [36]		6/12 mm double-glazed glass and 6/12 mm Low-E glass [37]	6/12 mm double-glazed glass and 6/12 mm Low-E glass [37]	6 mm single low-e [38]
	Installing adjustable angle sun shading devices, interior sun shading curtains or blinds [40,41]				
Roof system retrofit	EPS, XPS, Rock wool board, Vacuum insulation plate (The thickness of the insulation layer can be referred to Figure 16)				
	Rooftop photovoltaic system [31]				
Lighting and Control System	CFLs and LEDs [22], electronic ballasts [47]				
	Fully automatic control [48]				
HVAC and other building equipment systems	Vertical single-pipe system [26], Ground-Source Heat Pump (GCHP) systems [24,29], Clean heating equipment [50,51]		All DC inverter air conditioners [59], solar domestic hot water systems [24]	All DC inverter air conditioners [59]	All DC inverter air conditioners [59]
	Intelligent temperature control system [47]				
	Mechanical Ventilation Heat Recovery (MVHR) [28,32], Dedicated Outdoor Air Systems (DOAS) [55]				

The current research framework on sustainable retrofitting of residential buildings in China requires revision. Additionally, significant differences exist among different climatic zones in terms of building characteristics, economic conditions, and climate factors. Researchers have proposed an optimization method for decision-making on existing building retrofit strategies based on Net Present Value (NPV) analysis [48,90]. They have established a comprehensive optimization framework for energy efficiency and cost-effectiveness and have concluded that:

(1) In cold regions of China, achieving 60% energy savings can result in the highest optimal Net Present Value (NPV) [90].
(2) In severely cold regions of China, the optimal energy savings target may be 50%, as both 60% and 50% energy savings yield the same maximum Net Present Value (NPV) [90].
(3) In hot-summer and cold-winter regions of China, the maximum benefit in terms of Net Present Value (NPV) can be achieved by targeting a 40% energy savings [48].
(4) According to the JGJ75-2012 "Energy Efficiency Design Standard for Residential Buildings in Hot Summer and Warm Winter Zones", energy savings of up to 50% can be achieved [101].
(5) In temperate regions of China, the maximum benefit in terms of Net Present Value (NPV) can be achieved by targeting 30% energy savings [48].

Their specific modifications are shown in Table 10.

This retrofitting framework, constructed based on simplified climate models, applies to typical regions within different zones, notably in the central regions where climatic conditions markedly diverge from other climate zones. However, in areas where multiple climate zones intersect, the climatic conditions are often challenging to define, necessitating an assessment of the retrofitting benefits precisely. Consequently, building performance simulation tools becomes imperative to simulate the outcomes of retrofitting measures.

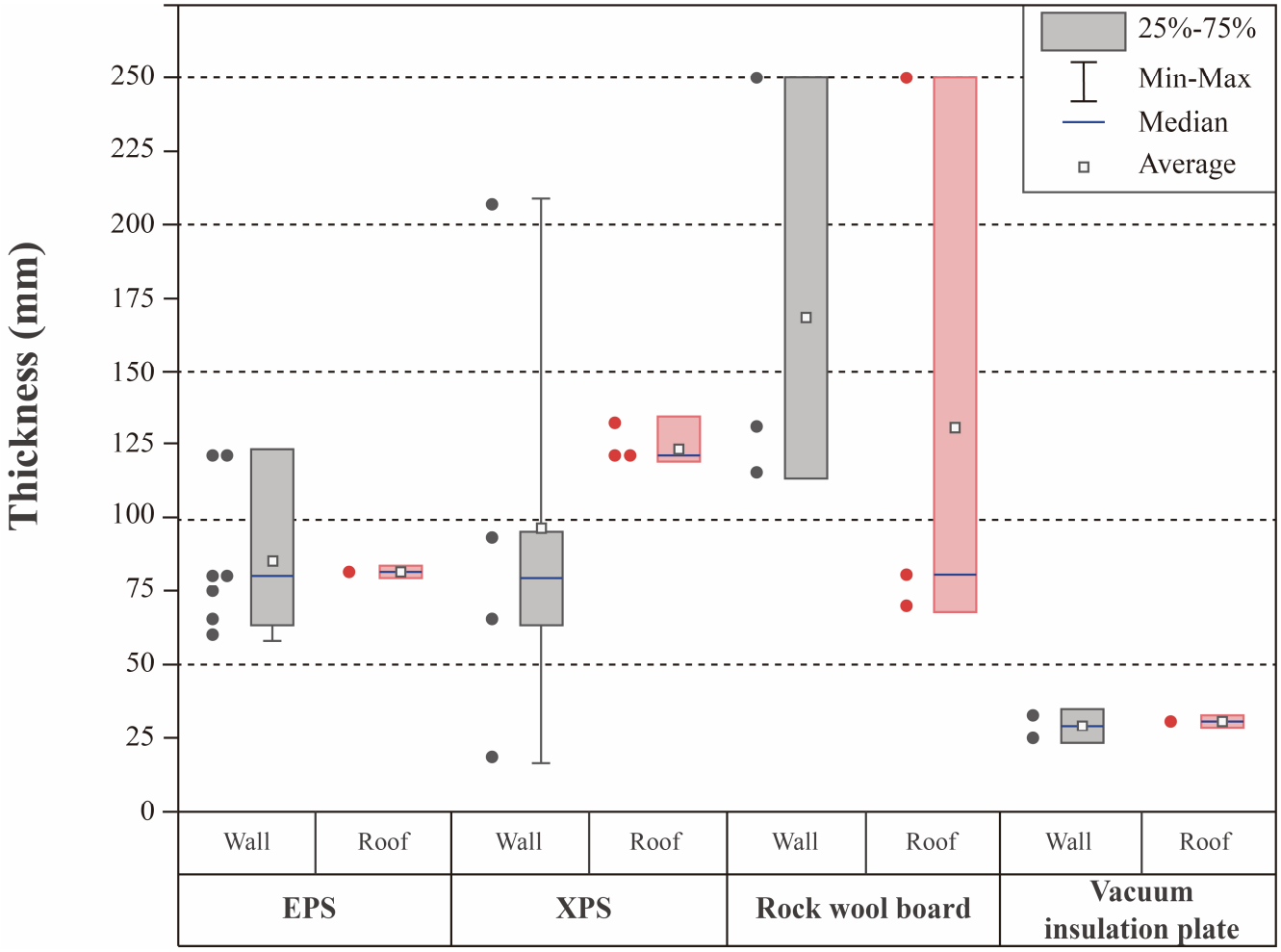


Figure 16. Review the material and thickness of wall and roof insulation mentioned in the literature [23,25–28,30–32].

Contemporary building performance simulation software encompasses nearly all possible pathways for residential building retrofitting, ranging from envelope structures to building equipment systems. DesignBuilder and EnergyPlus have emerged as the most favored Building Energy Modeling and Simulation (BEMS) tools owing to their accuracy and relative user-friendliness. However, EnergyPlus necessitates integration with other simulation-based software such as Autodesk REVIT and SketchUp. Researchers often integrate specific building performance simulation software with optimization programs using programming languages like MATLAB to address the scarcity of integrated tools combining thermal physics and optimization. Genetic algorithms, notably the NSGA II algorithm, are commonly employed due to their convenient architecture for interfacing with building performance simulation tools and managing their outputs.

The objective of suitability assessment is to determine the optimal building structure to be implemented. Consequently, the optimization process should also consider legal mandates and implicit rating constraints.

Sustainable building certification offers a comprehensive assessment of building performance, including environmental impacts. These certifications evaluate and rate buildings' performance and environmental impacts, encouraging the adoption of more environmentally friendly measures within the building sector. Numerous assessment systems exist, with LEED, BREEAM, and CASBEE considered the most relevant. Moreover, combining lifecycle assessment (LCA) with multi-objective decision optimization is pivotal in evaluating both the environmental and economic benefits of sustainable retrofitting. Prototype

model library decision assessments are often utilized to identify local prototype models and determine the energy microclimate of retrofitting targets, serving as primary tools for suitability assessment. The involvement of stakeholders, particularly governmental bodies, energy service companies, and residents, is increasingly garnering attention within the academic community.

Table 10. Retrofit Strategies for Optimal Energy Savings Targets by Region [48,90].

Building Systems	Groups of Retrofit Options	Cold Zone (60% Energy Saving [48])	Severe Cold Zone (50% Energy Saving [48])	Hot-Summer and Cold-Winter Zone (40% Energy Saving [90])	Temperate Zone (30% Energy Saving [90])
External wall system	T1—Insulation on south	50 mm EPS	50 mm EPS	30 mm EPS	30 mm EPS
	T2—Insulation on north	50 mm EPS	50 mm EPS	30 mm EPS	30 mm EPS
	T3—Insulation on east	100 mm EPS	50 mm EPS	30 mm EPS	30 mm EPS
	T4—Insulation on west	50 mm EPS	50 mm EPS	30 mm EPS	30 mm EPS
Window and shading system	T5—Window retrofit on south	6/12 mm double low-e	6/12 mm double low-e glazing	6/9 mm double glazing	No retrofit
	T6—Window retrofit on north	6/12 mm double low-e	No retrofit	6/12 mm double low-e glazing	6 mm single low-e
	T7—Window retrofit on east	6/12 mm double low-e	No retrofit	6/12 mm double low-e glazing	6/12 double low-e glazing
	T8—Window retrofit on west	6/12 mm double low-e	6/12 mm double low-e glazing	6/12 mm double low-e glazing	6/12 double low-e glazing
	T9—Shading on south	No retrofit	No retrofit	No retrofit	No retrofit
	T10—Shading on north	Venetian blind	No retrofit	Venetian blind	No retrofit
	T11—Shading on east	No retrofit	No retrofit	Venetian blind	No retrofit
	T12—Shading on west	Venetian blind	No retrofit	270 mm overhang	Venetian blind
Lighting and control System	T13—Daylighting control	Fully auto-control	Fully auto-control	No retrofit	Fully auto-control
	T14—Lighting occupancy control	Fully auto-control	Fully auto-control	Fully automatic control	Fully auto-control
	T15—Constant lighting control	No retrofit	No retrofit	Fully automatic control	No retrofit
	T16—Lighting lamps	LED	LED	LED	LED
HVAC and other building equipment systems	T17—Heating system	Pipe system retrofit	Pipe system retrofit	Using inverted air conditioner with 3.5 cop	No retrofit
	T18—Cooling system	No retrofit	No retrofit	No retrofit	No retrofit
	T19—BEM system	B-adapting operation	C-adapting operation	No retrofit	No retrofit
	T20—Solar water heater	No retrofit	200 L solar water heater	No retrofit	No retrofit

This study aims to provide comprehensive insights into the status of sustainable retrofitting in Chinese residential architecture, with the intention of aiding policymakers, designers, and researchers in understanding the challenges of implementing retrofit plans. Additionally, it seeks to facilitate the development of more efficient retrofit policies and strategies in the future. The study outlines potential assistance for designers, researchers, and policymakers as follows:

(1) Designers can select suitable building performance simulation software based on project requirements, optimizing their design and operation before implementation. Given that designers often utilize simulation tools such as Autodesk REVIT and SketchUp in the initial design phase, EnergyPlus, with its advantages of compactness and user-friendliness, can be considered the preferred choice. Assisting designers in understanding commonly used assessment systems like LEED and BREEAM, along with their underlying evaluation methods, can facilitate the establishment of clear design logic during the design process.

(2) Researchers at universities and research institutions can delve into learning simulation software relevant to their respective fields of study. For instance, computational fluid dynamics (CFD) tools like FLUENT are commonly used for buildings' natural ventilation and airflow analysis. At the same time, Ecotect Analysis is utilized for acoustic environments, and HelioScope and Integrated Environmental Solutions Virtual Environment (IES-VE) are preferred for photovoltaic systems. Additionally, acquiring knowledge in multi-objective optimization, lifecycle assessment, and prototype model library decision evaluation methods can aid in understanding the current assessment systems and assist in redefining suitable evaluation frameworks.

(3) Policymakers within typical climatic regions can formulate local, sustainable retrofit policies based on the summarized retrofit framework. For policymakers in atypical climatic regions, refining the retrofit framework can aid in crafting more precise retrofit policies. Moreover, policymakers can utilize a combination of lifecycle assessment (LCA) and multi-objective decision optimization to establish appropriate indicator systems for comprehensive evaluation and analysis of the effectiveness of building energy retrofitting. This approach can guide the formulation of environmental and economic policies within the local building sector.

However, the current research still has several significant limitations, primarily covering the following aspects:

(1) The framework for renovation in this study is based on simple climate models, which may lead to significant errors at the edges of climate zones. A more precise climate model is necessary to reflect the actual conditions for renovation accurately.

(2) The current study utilizes static timetables to depict the interaction between users and building systems. These static timetables fail to capture the stochastic nature of user behavior, leading to significant disparities between actual and simulated energy usage in buildings. This performance gap hampers the effectiveness of building performance simulation tools.

(3) The current study lacks a comparison of the differences and significant impacts of existing residential building renovation policies among representative provinces in thermal zones.

(4) Due to constraints on article length, our study did not assess the adoption level of intervention measures in sustainable retrofitting of residential buildings. Instead, we conducted a straightforward review of retrofit measures reported in the literature without determining whether specific intervention measures were adopted or rejected under particular conditions.

Possible solutions to address the current limitations include:

(1) Coupling building performance simulation tools with urban microclimate simulation tools facilitates rapid and accurate exchange of information between urban microclimate and building energy models, enabling the generation of more realistic building energy simulation results that cannot be obtained through separate simulations.

(2) Due to the stochastic nature of human behavior, effective modeling of user behavior can be achieved through stochastic models. Therefore, integrating building performance simulation tools with stochastic models is a viable solution for modeling user behavior in building performance simulations.

(3) Conducting a comprehensive assessment of the differences between the renovation policies and actual measures in the major cities of each thermal zone is recommended. This will help identify the most suitable technical solutions for sustainable renovation of existing residential buildings in China that truly align with local conditions.
(4) In order to determine the adoption or rejection of specific intervention measures, evidence should be provided based on the building's climate zone, use (residential, mixed-use, etc.), construction year, and existing performance analysis to ascertain the technologies employed.

Building upon this recommendation, future research will delve into exploring the existing simulation tools for energy, climate, and user behavior, along with coupling strategies, to comprehensively analyze the effectiveness of sustainable renovation. This effort will aid in integrating the most promising tools into the existing research framework to support comprehensive energy and environmental renovation design, ultimately achieving sustainable renovation of existing residential buildings in China.

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