The Early-Stage Decision-Making of Modular Façade Retrofitting with Renewable Energy Technologies
– A Case-Based Reasoning Approach

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Abstract

Energy conservation and emission reduction are pressing global priorities, with buildings being a major energy consumer. Retrofitting existing structures offers significant potential to reduce energy use and carbon emissions. The Climate Change Act 2008 set the 2050 Net-Zero target, which requires the UK government to reduce the greenhouse emissions by 100% relative to 1990 levels for 2050. To further distribute this aim, the targets in retrofit are raised for at least a 32% share of renewable energy and at least a 32.5% improvement in energy efficiency. Approximately 27 million existing residential buildings need to be retrofitted in the UK. However, meeting national carbon goals within tight timelines is difficult due to the massive scale of housing.

Modular retrofitting, which involves upgrading existing structures with prefabricated, modular components, holds great promise for improving building functionality, energy efficiency, and aesthetics without the need for complete demolition. This method is generally faster, less disruptive, and more cost-effective than traditional renovation methods. Post-war housing in the UK, often standardized and mass-produced, is particularly suitable for modular retrofits, integrating renewable technologies and improving energy efficiency. However, modular retrofitting is still underdeveloped, with most studies focusing on individual cases rather than scalable, broad-based solutions. Key barriers include housing diversity hindering universal strategies, insufficient systematic research linking modular designs, and a lack of stakeholder awareness.

This research aims in developing a Case Based Reasoning (CBR) decision-making approach, encourage practitioners to consider potential applicable modular retrofit approaches rapidly, by providing the matched similar solutions on the renewable technologies in the early design stage.

There are 2 research questions related to this aim:

1. What kind of mechanism can enable the CBR decision-making approach to achieve rapid selection of renewable energy technologies?
2. How to translate the knowledge of modular retrofit with renewable energy technologies into an integrated guide?

Methodology: This research addresses these challenges by proposing a Design Research Methodology (DRM) to systematize retrofit design processes. By establishing structured research frameworks and methodological selection criteria, which could facilitate data-driven decision-making. A comprehensive repository of retrofit solutions permits comparative analysis and solution integration, while early-stage selection of renewable technologies streamlines retrofit workflows.

This research pioneers a Case-Based Reasoning (CBR) decision-support framework, empowering practitioners to rapidly identify applicable modular retrofit strategies. Through pattern recognition in historical retrofit data, the CBR system provides context-specific renewable technology recommendations during critical early design phases. A CBR decision-support prototype for rapid retrofit strategy matching is constructed.

The scalability of the research lies in its ability to transition from fragmented case studies to replicable, system-level interventions. By addressing the gaps in current approaches, the research establishes theoretical foundations that allow for more widespread and efficient implementation of sustainable building solutions. This scalable framework can be adapted across various contexts, making it possible to replicate successful interventions in diverse settings, ultimately driving broader adoption of sustainable technologies in the building sector.

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1 Introduction

1.1 Background

With the increase of social development, almost 42% of the CO2 emissions were produced by buildings annually all over the world (Global Status Report 2017, 2017). Numerous studies have been conducted focusing on reducing energy usage and carbon emissions in the building sector, especially in Europe. The Danish government plans to eliminate fossil fuel dependence by 2050, primarily through enhancing energy efficiency (International Energy Agency, 2021). As the global building stocks becomes saturated, building energy retrofitting is receiving increasing attention as an efficient method to improve energy efficiency. The US government plans to invest a trillion dollars in the building energy efficiency renovation field, (Fulton & Grady , 2012) which is expected to reduce about 616 million metric tons of CO2 emission per year. (U.S. Census Bureau, 2018) The Climate Change Act 2008 (Climate Change Act 2008, 2008) established the 2050 Net-Zero target, requiring the UK government to reduce greenhouse emissions by 100% relative to 1990 levels by 2050. To support this aim, retrofit targets include a minimum 32% share of renewable energy and at least a 32.5% improvement in energy efficiency (Du, et al., 2019). Achieving this goal will require retrofitting approximately 27 million (Ministry of Housing,C.&L.G., 2016) existing residential buildings in the UK.

Building envelope retrofit is one of the main solutions for achieving architecture energy efficient purposes, which has the advantage of convenience and performance (Du, et al., 2019). Approximately 50% of building energy consumption relates to building envelopes (Mavromatidis, et al., 2013). Building envelope to reach energy saving objective follows two principles reducing energy loss and improving energy obtainment. (Roberti, et al., 2017; Jafari & Valentin, 2017) Traditional renovation manner primarily adopts the reducing energy loss method such as adding insulation material, increasing relative material thickness, etc. Compares to the traditional approach, some innovative emerging approaches aim to integrate renewable energy techniques into building envelopes, such as applying solar photovoltaic systems on the façade constructions. (Gahrooei, et al., 2016) Consequently, to get optimal energy-efficient performance, both two aspects should be considered in the retrofit process.

Architects and building owners are often facing challenges in selecting the appropriate retrofit approaches, especially when considering multiple objectives as many of them are complicated and conflicting (Ma, et al., 2023), such as costs, construction time, energy collection or performance, etc. The decision-making process could broadly be classified into traditional design approaches and emerging design approaches. In Deb and Schlueter's research, they summarized these two ways as "Bottom-up approach" and "Top-down approach" (Deb & Schlueter, 2021). While a precise first adoption for this specific application is hard to pinpoint, the terminology and application of these strategies to modular design and construction were described in research by 2004. Such as the research done by Kohler & Hassler (2002), Sun & Zhang (2004), and Kudsk, Hvam, & et al. (2013), provided the understanding of how “top-down” and “bottom-up” strategies apply to modularization. The traditional design approach refers to the “Bottom-up approach” as it requires the measurement and analysis of fundamental details for individual target that lead into a specific retrofit strategy. It is a typical workflow that commonly used in building retrofit, which ensures the accuracy of the targeted case but requires sufficient work in the early design stage for not only survey and project setup but also energy auditing and performance assessment (Ma, et al., 2012). On the other hand, the emerging design strategy, “Top-down approach”, is benefit from the significant development from AI machine learning and data mining (Deb & Schlueter, 2021). It usually uses algorithms to manipulate input to achieve certain goals.

As the traditional Bottom-up approach is limited by experiences of experts who determine the trade-offs (Ma, et al., 2023). As Czmoch and Pekala argues, which often rely on manual processes and limited case studies for inspiration, struggle to be applied effectively to large-scale or complex projects because the specific examples or "cases" used for reference are often not representative or adaptable enough to handle increasing complexity. This leads to time-consuming analysis, difficulty visualizing the final product, and potential design conflicts that hinder growth and efficiency (Czmoch & Pekala, 2014). In this case, parameter design methods and decision-making tools, which can avoid this limitation, increasingly attract the attention of designers.

To implement the Net-zero energy goal by 2050 (Climate Change Act 2008, 2008) is a global challenge, and building retrofit plays an essential role among it. Under the recent international affairs happened in 2022, the escalation of energy consumptions, costs, and the scarcity of energy especially in Europe, urges the development of new approaches or tools to accelerate of the building retrofit and energy reduction. In this case, some solutions related to artificial intelligence should be proposed to fill the gap. Translating professional knowledge into directly displayable approaches, which enables stakeholders to rapidly understand the potential retrofit solutions close to their demands. To improve the efficiency of decision-making in early design stage.

This research analyses one of the AI solution, Case-Based Reasoning (CBR), utilised during building retrofitting, to coordinate with the traditional design scheme. The Case-Based Reasoning is an experience-based approach based on artificial intelligence (AI) and machine learning, firstly proposed in 1971 by Kling (Kling, 1971). CBR means using previous experiences or existing cases to solve new similar problems (Kolodner, 1992). Currently, it has been widely implemented in many fields to support decision-making, such as the graph recognition (Perner, 1999; Hamza, et al., 2007; Zahed, et al., 2016), medical science (Nilsson & Sollenborn, 2004; Holt, et al., 2005; Bichindaritz, 2008; Pusztová, et al., 2019; Sappagh & Elmogy, 2016), etc.

But in terms of its application to buildings, especially in retrofit, not enough attention has been paid to it (Matthew, 2010). Relative research has been done so far mainly focused on specific building issues such as construction cost, case search, etc. (Asad, et al., 2012; Ahn, et al., 2020). Nevertheless, CBR contains many details in the calculation section that straight influences the final output precision. Existing investigations adopt various approaches to correct the CBR process to improve accuracy (Fu & Shen, 2004; Méndez, et al., 2007; Ji, et al., 2010; Guo, et al., 2011).

1.2 Current Situation for Energy Reduction and Building Retrofit

1.2.1 Attempts and Goals for Energy Reduction and Low-Carbon Economy

In Europe, building renovation activity accounts for 29% of the construction sector. It is currently driving growth in the housing market, which is more than new construction projects. Approximately, it accounts around 18% of industry activity (Eurostat 2022; FIEC 2023). This trend reflects the EU's strategic that focus on decarbonising existing buildings through initiatives, such as the Retrofit Wave, which aims to double the annual energy retrofit rate by 2030 (European Commission 2020).

In Spain, the Housing Ministry reports that the building stock is around 25 million dwellings, of which 68% are classified as primary dwellings and 32% as secondary or non-primary dwellings (Du, et al., 2019). During the 2010 operational phase, the construction sector accounted for 26.1% of annual energy consumption, of which residential use accounted for 17.5% and commercial buildings accounted for 8.6%. Heating systems dominate energy demand, accounting for 42.5% of total consumption, followed by hot water generation (19.6%), equipment operation (19.4%), lighting (9.6%) and cooling (8.9%) (Guo, et al., 2011).

In this context, a systematic review of the existing building is essential to assess current energy performance and implement targeted measures to reduce the impact of environment. Among the existing EU building stock, as BuiltHEAT demonstrated in their report (BuildHEART, 2015), a 1~1.5% annual retrofit rate is insufficient to achieve the 2050 goal (European Commission, 2025). Retrofitting existing structures - rather than relying on tougher new building regulations - is the most viable strategy for meeting low-carbon targets.

1.2.2 Existing Situation for Sustainable Retrofit

In the past decade, the global building energy efficiency transformation has formed a multi-level promotion pattern. Government agencies and international organizations continue to promote the energy efficiency of existing buildings through policy guidance, financial support and technology research and development. In the United States, the federal government will strengthen its support for existing building renovation through special grants in 2023 (U.S. Environmental Protection Agency, 2023), and the commercial building energy Efficiency Disclosure system implemented in Australia since 2010 (Precious, 2022) requires owners of large commercial buildings to publicize energy consumption data to transaction parties. As early as the fiscal year 2009-2010, the Queensland government invested 8 million Australian dollars in the energy-saving renovation of public buildings (Queensland Treasury, 2009), and the British government set a target of achieving "100% reduction in greenhouse gas emission by 2050" compared to the level of 1990 (Nuala & Iona, 2025), which set a carbon budgets goal in 7 stages, indicated a “26% reduction on 1990 levels” from the first stage 2008~2012, .

The International Energy Agency (IEA) has built a global collaboration network through a series of technical cooperation projects, and the 4 major technical routes it focuses on are typical examples:

- Annex 46: Holistic toolkit for retrofitting government buildings
- Annex 50: Prefabricated systems for residential renovations
- Annex 55: Reliability of retrofitting measures
- Annex 56: Greenhouse gas-optimized building renovations

These initiatives provide frameworks for policy, funding, and technical guidance to accelerate retrofitting.

In additional to policy efforts, extensive research has identified retrofit strategies to reduce energy use in existing buildings. Studies confirm that retrofitting—defined as upgrades to aging or degraded structures—can significantly lower energy consumption and greenhouse gas emissions (Ma, et al., 2012).

According to these efforts, retrofit research focuses on 3 key approaches:

1. Passive Methods: Techniques like Trombe walls, ventilated façades, and glazed walls, which may require partial reconstruction.
2. Renewable Integration: Innovative process of bringing renewable energy sources into the existing power grid or into mechanical systems, which demand tailored designs.
3. Efficient Mechanical Systems: The design and implementation of mechanical systems (like heating, ventilation, hot water preparation, etc.) to operate with minimal energy waste.

The renewable integration and efficient mechanical system are closely related and often work together to achieve better energy efficiency.

The focus of modular retrofitting for this thesis mainly linked to IEA Annex 50 mentioned above, which is for Prefabricated systems for residential renovations. Du et al. argued in their research that modular retrofitting—emphasizing prefabricated, adaptable components—has emerged as a cost-effective solution for diverse building typologies (Du, et al., 2019). By combining insulation, renewable integration and standardized workflows, the modular system simplifies installation while maximizing energy savings. At present, most research are limited to the development of a single technology, and a systematic transformation model covering the whole process of design-production-construction has not been established, which has become a key challenge restricting the large-scale development of the industry.

1.2.3 Needs for Energy Efficient Retrofit

While green-building technologies are now widely implemented in new constructions, the sustainable use of existing buildings hinges on their adaptability to evolving demands. Over time, aging structures face challenges such as deteriorating infrastructure, obsolete equipment, outdated functional layouts, and inadequate thermal comfort (Dabous & Hosny, 2025).

Retrofitting the existing residential stock to achieve sustainable development and zero-energy standards presents both opportunities and challenges (Capeluto & OChoa, 2014). Research into new systems that strategically apply energy-saving strategies can yield significant reductions in consumption, while expanding retrofitting options must be integrated into national construction policies. Such retrofits not only reduce energy use and emissions but also enhance occupants' thermal comfort.

Furthermore, energy renovations can increase a property's market value and appeal, incentivizing private investment in sustainability.

1.2.4 Challenges for Current Energy Efficient Retrofit

Despite certain motions have been taken, however, from the current retrofitting practices, there are still a variety of challenges remaining. For instance, most retrofit solutions in used now only target in thermal insulation. Furthermore, heat loss through the building envelope stands for “more than 75% of the total heat loss” in UK climate (UK Climate Change Act 2008, 2009).

The technical feasibility of the deep reconstruction measures is of great significance for improving the reconstruction effect. However, the purpose of many reviews of technical challenges is to assess what is feasible or technically appropriate in each situation. In recent years, several literatures focus on the technical solutions of deep transformation. In particular, the focus is usually on integration packages designed to improve performance, while reducing the time and complexity of interventions, combined with modifications to a containment structure and HVAC system.

Challenge also exists in prefabricated systems. Such as limited design options or adaptation to unexpected geometric shapes, and a generic appearance regardless of location. Because of the lack of a coherent approach to defining energy strategies, most systems lack the ability to adapt to the needs of different climatic zones (Capeluto & OChoa, 2014).

Another challenge is that even if the characteristics of the original building are incompatible with energy efficiency, the result must be as close as the new one. In addition, due to the enormous impact of the built environment on energy consumption and emissions, old buildings need to be retrofitted to give them the flexibility to cope with possible climate change and the resulting new energy use patterns (Capeluto & OChoa, 2014). As the number of buildings affected is extremely large, it is necessary to adopt different methods from traditional renovation to achieve energy conservation and emission reduction in a long time. The traditional renovation method has prolonged the execution time and the destruction of the residents' lifestyle. Therefore, punctuality may be more appropriate.

Rapid improvements in the energy efficiency of existing buildings are therefore essential to timely reduction of global energy use and to promote environmental sustainability. Retrofitting existing buildings presents an important opportunity to reduce global energy consumption and greenhouse gas emissions. This is an efficient solution to achieve sustainability in the built environment at a relatively low cost and a high rate of adoption. Although a variety of retrofit technologies are available, the method of identifying the most cost-effective retrofit measures for specific projects remains a major technical challenge. Systematic selection and determination of the best retrofit scheme for existing buildings can help reduce the energy consumption of buildings (Ma, et al., 2012). One option is to start with the facade, as the residential envelope accounts for 20-30% of the total energy consumption (UK Climate Change Act 2008, 2009).

On the other hand, European research in the field of adaptive building envelopes is coined by numerous nationally funded projects and a lack of knowledge transfer between the individual research institutes amongst each other and the industry (Du, et al., 2019). Du et al also argue that "a selection of renewable technologies and its decision-making tool could be a crucial part for ongoing development" (Du, et al., 2019). In this context, more systematic research and establishment of evaluation criteria will facilitate knowledge transfer between individual research institutions and between industries.

According to the previous existing attempts by other researchers, this research would conduct the criteria for evaluating different design work would be organized and developed into a more systematically benchmark, which would be a better solution to not only mapping out the whole story of the reason why modular approach for retrofit is more optimised, but also to tackle the challenges/gaps occurred from the existing approaches. And those identified challenges can be take into the next step of development.

1.3 Research Aim & Objectives

1.3.1 Research Aim & Research Questions

This research aims in developing a Case Based Reasoning (CBR) decision-making approach, encourage practitioners to consider potential applicable modular retrofit approaches rapidly, by providing the matched similar solutions on the renewable technologies in the early design stage.

Thus, there are 2 research questions related to this aim:

1. What kind of mechanism can enable the CBR decision-making approach to achieve rapid selection of renewable energy technologies?
2. How to translate the knowledge of modular retrofit with renewable energy technologies into an integrated guide?

These 2 questions have been researched and answered in this thesis.

Question 1 is answered in Chapter 3 & 4. Question 2 has been answered mainly in Chapter 5.

The research work has been published in “Building and Environment”, “Energy and Buildings”, “Energies” and “International Journal of Low-Carbon Technologies” during research period. Detail of those 4 journal publications is listed in Publications.

1.3.2 Research Objectives

The growing emphasis worldwide on retrofitting existing buildings to achieve energy efficiency highlights both progress and the challenges that exist.

To address these challenges, this study aims to achieve the following objectives:

a. To comprehensively analyse the present situation (building-integrated renewable energy technologies, existing retrofit methodologies, practical challenges, etc.) by synthesising insights from literature reviews and case studies in the field of modular energy-efficient retrofit

b. To establish a database of the existing available building integrated renewable technologies for modular retrofit design based on the case studies.
c. To develop a user interface--introduce matching potential retrofit solutions and translate the knowledge of modular retrofit with renewable energy technologies into an integrated guide for stakeholders to refer to.

1.4 Research Novelty

The distinctive feature of this research lies in its triple innovation of the system gaps existing in the practice of building modular retrofit.

First, it pioneers a holistic methodology that transcends conventional single-case retrofit analyses by integrating modular design principles with data-driven scalability.

Second, it introduces a prototype Case-Based Reasoning (CBR) decision-making support tool, embedding the selection of modular retrofit with renewable energy technologies into early-stage retrofit planning. This AI-augmented tool dynamically adapts historical retrofit data to new contexts, reducing the delay in the design stage and achieving efficient integration of renewable energy based on demand.

Third, the research redefines stakeholder engagement as a co-design process, bridging the persistent divide between technical solutions and practical applications. It is a critical advancement beyond the top-down, technology-centred approach.

The novelty lies in the synergistic convergence of these elements:

1. Systemic scalability: The DRM-CBR framework shifts retrofitting from fragmented case studies to replicable, mass-market solutions.
2. Early-stage renewable integration: By prioritizing the potential renewable technologies during initial design (rather than post-construction), the methodology circumvents costly retroactive modifications.
3. Translation of knowledge: The actionable User Interface (UI) translates the professional knowledge into a straightforward display of potential constructions of the recommended module with renewable energy systems, which enables stakeholders without architectural backgrounds to participate in the early design and decision-making.

This work not only advances academic discourse but also delivers actionable tools to transform the building sector's role in global climate mitigation. Its interdisciplinary approach—merging modular engineering, AI-driven decision science, and social innovation—positions it as a benchmark for scalable, stakeholder-aligned retrofitting in the post-carbon era.

1.5 Thesis Structure

This thesis is structured to systematically address the research objectives through a logical progression from foundational theory to practical implementation and critical evaluation. The chapters are organized as follows:

- Chapter 1 Introduction: Establish the research context, objectives, and significance of modular retrofits in achieving EU decarbonization targets. It outlines the gaps in current situation and introduces the proposed Case-Based Reasoning (CBR) approach as a novel solution.
- Chapter 2 Methodology: Present the overarching Design Research Methodology (DRM), detailing the mixed-methods framework that integrates quantitative data analysis, stakeholder engagement, and iterative prototyping.
- Chapter 3 Literature Review: Critically examine existing scholarship on modular design, building retrofits, and multi-criteria decision-making systems, identifying key challenges and opportunities for CBR integration.
- Chapter 4 Case-Based Reasoning Approach: Explore the theoretical and technical foundations of the CBR model, including workflow design, attribute weighting mechanisms, and input-output architectures tailored for retrofit decision-making.

- Chapter 5 Prototype of CBR Decision-Making Support: Develop and describe a functional prototype of the CBR tool, addressing limitations in case diversity and data granularity while emphasizing user-centric interface design.
- Chapter 6 Discussion: Evaluate the prototype's efficacy against real-world retrofit scenarios, discuss findings in the context of EU policy goals, and reflects on theoretical and practical implications.
- Chapter 7 Conclusion: Synthesize key contributions, limitations, and recommendations for future research, emphasizing the role of CBR in scaling modular retrofits globally.

This structure ensures a cohesive narrative, where each chapter builds on the preceding one—transitioning from problem identification and theoretical grounding (Chapters 1–3) to methodological innovation (Chapters 4–5) and culminating in synthesis (Chapters 6–7). The following chapter, *Methodology*, elaborates on the DRM framework, setting the stage for the interdisciplinary exploration of modular retrofit challenges.

1.6 Summary

In this chapter, firstly introduce the overall background of achieving energy conservation worldwide, to understand emission reduction and building energy efficiency retrofit become an essential goal in construction sector. Through understand the current situation and need for building retrofit, to find out the challenges encountered, which is how to select and determine the retrofit scheme for the existing building more quickly and systematically.

To solve these existing challenges, the aim and research questions of this thesis are introduced. This research aims in developing a Case-Based Reasoning decision-making approach, encourage practitioners to consider potential applicable modular retrofit approaches rapidly, by providing the matched similar solutions on the renewable technologies in the early design stage. The workflow to solve the 3 research questions, raised in section 1.3.1 Research Aim & Research Questions, conducts the structure of the thesis.

2 Methodology

2.1 Introduction

2.1.1 Design Research Methodology (DRM) in multi-criteria decision-making support for Modular Building Retrofits

To translate the knowledge of modular retrofit into an integrated guide. It is essential to conduct a systematical analysis and review the modular retrofit with renewable energy technologies, which could introduce the holistically approach to the users who would like to better understand and make the design decision for modular retrofit projects in the future.

Multi-Criteria Decision-Making Approaches for Building Retrofit establishes the theoretical foundation for evaluating retrofit strategies against conflicting objectives such as energy savings, cost-effectiveness, and occupant comfort. It underscores the need for systematic frameworks to navigate trade-offs between technical, economic, and social criteria. Building on this, establishing a Design Research Methodology for Modular Building Retrofits operationalises these principles by proposing a structured, iterative methodology that embeds multi-criteria decision-making into modular retrofit design.

Design Research Methodology (DRM) is a theory proposed by Blessing and Chakrabarti as a systematic methodology for doing design research (Blessing, et al., 2009). It is a structured, iterative framework tailored to address complex challenges in design work. Based on the review of literature and previous research, DRM was not explicitly mentioned in energy-efficient building retrofits. DRM could integrate data-driven decision-making, stakeholder collaboration, and scalable modular design principles to systematise retrofit processes. It emphasises practical solutions through phased research, validation, and implementation, ensuring alignment with both technical and socio-economic goals. DRM transforms fragmented retrofit practices into a cohesive, evidence-based methodology. By harmonising technical rigor with stakeholder needs, it accelerates the transition to low-carbon buildings while addressing urgent climate targets.

DRM consists of 4 stages: Research Clarification (RC), Descriptive Study I (DS I), Prescriptive Study (PS) and Descriptive Study II (DSII). (Blessing, et al., 2009)

1. RC—Research Clarification (review-based, filter preliminary criteria)

The first step is to clarify the research (RC stage) by reviewing the literature to determine the goals, priorities, and scope of the research project.

2. DS I—Descriptive Study I (considering as the network of influencing factors/ involve the reference model to setup the database)

Define success criteria/filter the key factors or bind the network based on this. After Comprehensive DS-I, there should be an Initial PS, to suggest how to use these findings to improve the design. An exception is Type I, where the focus of the DS-I is to determine the success criteria that can be used for design research.

3. PS—Prescriptive Study (propose the impact model)

Supported comprehensive development (comprehensive PS) should at least be based on the review of descriptive literature (review-based DS-I), followed by the initial DS-II to evaluate the resulting support.

4. DS II—Descriptive Study II (evaluation)

The comprehensive DS-II should be based on the comprehensive PS or the review-based PS to determine the background of the support to be evaluated and at least be accompanied by instructions on how to improve the support (Initial PS).

According to the theory of DRM working stages, the phased research framework of the CBR modular building retrofit of this thesis could be addressed as below:

- Stage 1(Research Clarification--RC):

  The main goal of this phase is problem definition & data aggregation. Based on the historical dataset compilation (e.g., energy audits, retrofit case studies, literature reviews), to identify the retrofit challenges, such as energy inefficiencies, stakeholder barriers.

- Stage 2(DS I): Pattern Recognition & Strategy Generalization

Case-Based Reasoning (CBR) is used for historical pattern matching to derive scalable retrofit strategies from different building inventories. To obtain the modular retrofit typologies

- Stage 3(PS): Decision-Support System Development

  By integrating multi-criteria decision analysis with CBR prediction methods and leveraging the CBR prototype with a user interface, rapid selection of potential technologies can be achieved.

- Stage 4(DS II): Validation

  Verify the results from the prototype demonstration to ensure solutions align with user needs and regulatory constraints.

The DRM explicitly addresses the complexities by integrating tools for multi-criteria decision making and predictive modeling to prioritize retrofit options based on dynamic weightings of energy performance, lifecycle costs, and risk resilience. For instance, during the Decision-Support System Development phase (Stage 3), stakeholders apply multi-criteria decision-making to compare modular solutions—such as prefabricated façades versus decentralized HVAC systems—against context-specific criteria (e.g., local climate, regulatory constraints). This ensures that the methodology not only aligns with multi-criteria theory but also translates it into scalable, actionable workflows for heterogeneous building stocks.

By bridging abstract decision-making models with practical modular design, the DRM exemplifies how multi-criteria frameworks can advance retrofit practices from fragmented case studies to replicable, system-level interventions.

Thus, the working of this thesis mainly includes 4 stages, as shown in Figure 1 Flowchart of Methodology:

Stage 1: Systematic Review (Research Clarification)—In this stage, the purpose is to fully investigate the existing research relevant to the topic, which need to be reviewed for further analysis.

- To analyze and reassess the retrofit methods and knowledge gained from other successful cases.
- To analyze the common multi-criteria decision-making support approaches.
- To investigate the retrofitted buildings and innovation projects related to building energy efficiency.

Stage 2: Database Setup (Descriptive Study I)—Mainly focus on extracting the valuable indicators and attributes and analyzing the comparable combinations for the foundation of CBR database. The analyzed case studies for the database in this stage is based on the selected projects from H2020, shown in Table 7. Horizon 2020 was the EU's research and innovation funding program (8^{th} Framework Programme (FP8)) from 2014-2020 with a budget of nearly €80 billion (Grove, 2011). It funds research, technological development, and innovation. It supports open access research results, so these open access reports of innovative projects (Table 7) in sustainable building retrofit can be obtained to analyze.

- To analyze the typical structure/targeted constructions/common techniques in different circumstances, etc.
- To categorize the technologies in terms of the modular façade structure of those renewable energy techniques, building energy consumptions, etc.

Stage 3: Tool Development (Prescriptive Study -- Prototype of CBR Decision-making support)—Implement of the selection tool interface, the main consideration of this stage is presenting the perform indicators in an easier way for the users to understand.

- To translate the professional knowledge into user input labels to develop retrofit scheme.
- To develop the selection/calculation process of the suitable retrofit solutions with Python programming: the basic strategy for this step is based on the CBR concept, which proposed by Kolodner (Kolodner, 1992). The core process for CBR cycle is retrieving the matching cases and sort them in ranking, shown in Figure 13. A demonstration of the CBR prototype will be provided in this stage as well.

Stage 4: Validation of proposed Retrofit solution (Descriptive Study II)—to evaluate the selected algorithm (AHP) and demonstrate the limitation of the system.

- To indicate the reference & evidence to show the selected algorithm for tool calculation is reliable.
- To demonstrate the program with a cross-validation method (further discussed in 2.5), to evaluate the proposed solution from AHP calculation is appropriate for the energy efficient retrofits.
- To identify the scope: Make clear definition between ranking and optimizations – fit most may not be the best.

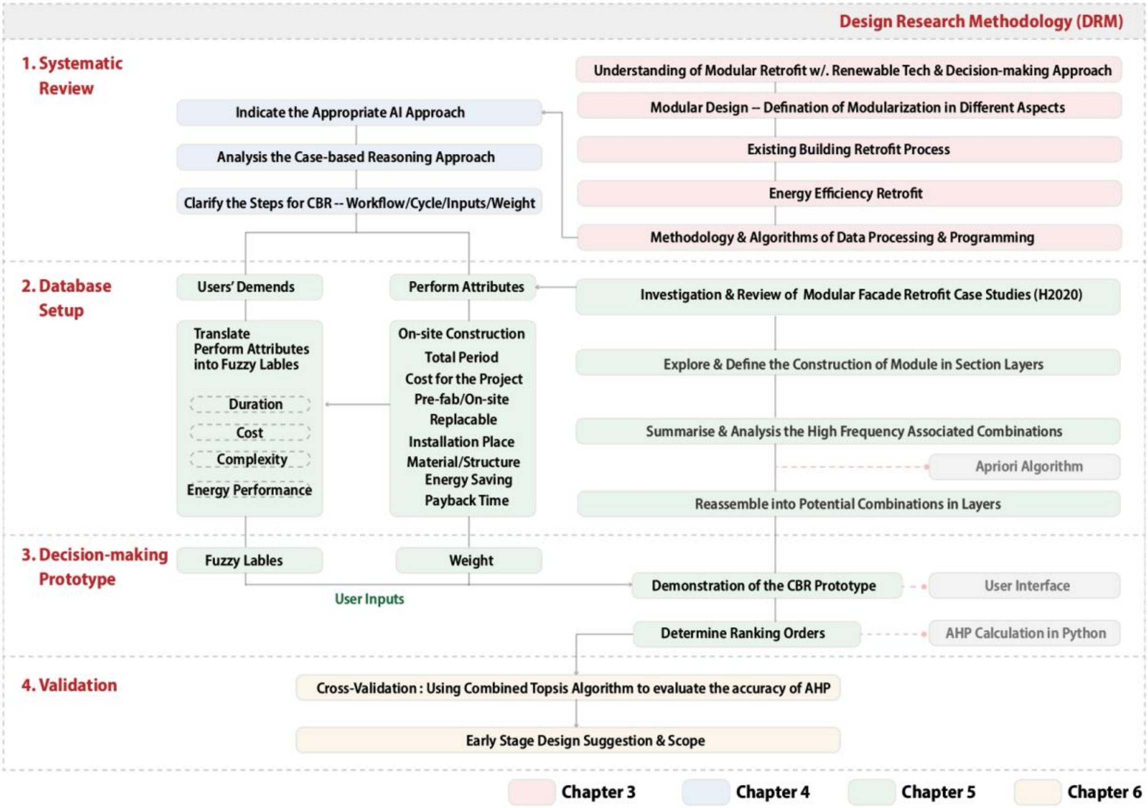


Figure 1 Flowchart of Methodology for this Thesis

[Image by Author]

2.2 Stage 1: Systematic Review

2.2.1 Literature Review

The literature review systematically combs the four core research areas, and gradually builds the methodology system of Case-Based Reasoning (CBR) modular retrofit. First, focus on the characteristics of the retrofit object, in-depth analysis of the particularity of the existing buildings in terms of spatial structure, functional requirements, and technical limitations, etc., to lay a theoretical foundation for the subsequent technical path selection.

In this context, the engineering value of modular construction technology is highlighted. In recent years, this technology has achieved breakthrough application in the field of building renovation with its advantages of flexible adaptation, controllable cost, and efficient construction. Its core lies in the prefabrication production of key components such as insulation layer and renewable energy interface, and the rapid on-site assembly through standardized nodes can shorten the construction cycle by 30%-50% (Du, et al., 2019), while reducing the interference to the normal use of the building. It is worth noting that the prefabricated modules for renewable energy production does not exist in isolation, and its performance needs to form synergies with passive energy-saving design and active energy systems.

The research of the existing modular retrofit system with renewable technologies reveals two optimization directions: On the one hand, the improvement of thermal performance of the envelope structure is still the basis of energy efficiency transformation (Fereidoni, et al., 2023). Hailu explains that the envelop structure involving the optimization of external insulation layer, high-performance door and window replacement and other technologies (Hailu, 2021); On the other hand, Hailu also mentioned, renewable energy integration technologies such as photovoltaic roofing and ground source heat pumps have gradually become the standard for retrofits, but there are common problems of inadequate system matching (Hailu, 2021);. Du et al. also points out that the current retrofit decision-making is faced with the dilemma of multi-objective conflict - cost control, energy efficiency improvement, comfort assurance and other indicators often have a relationship, and scientific decision support tools are urgently needed (Du, et al., 2019).

Based on this, this study innovatively introduces Case-Based Reasoning (CBR) approach to build a decision model. The theoretical advantage of this method is that by establishing a modular retrofit case database, the empirical data such as technical attributes and implementation effects of historical projects are systematically integrated. When facing with new retrofit tasks, the system can match existing cases based on similarity algorithm, extract proven solutions, and make adaptive adjustments. This experience-driven decision-making mode effectively solves the contradiction between the limitation of subjective experience and the separation of objective data in the traditional method and provides an operable and reliable decision-making path for complex transformation scenes.

To maximum the investigate on valuable research, the workflow of how to select the proper research materials are shown in Figure 2.

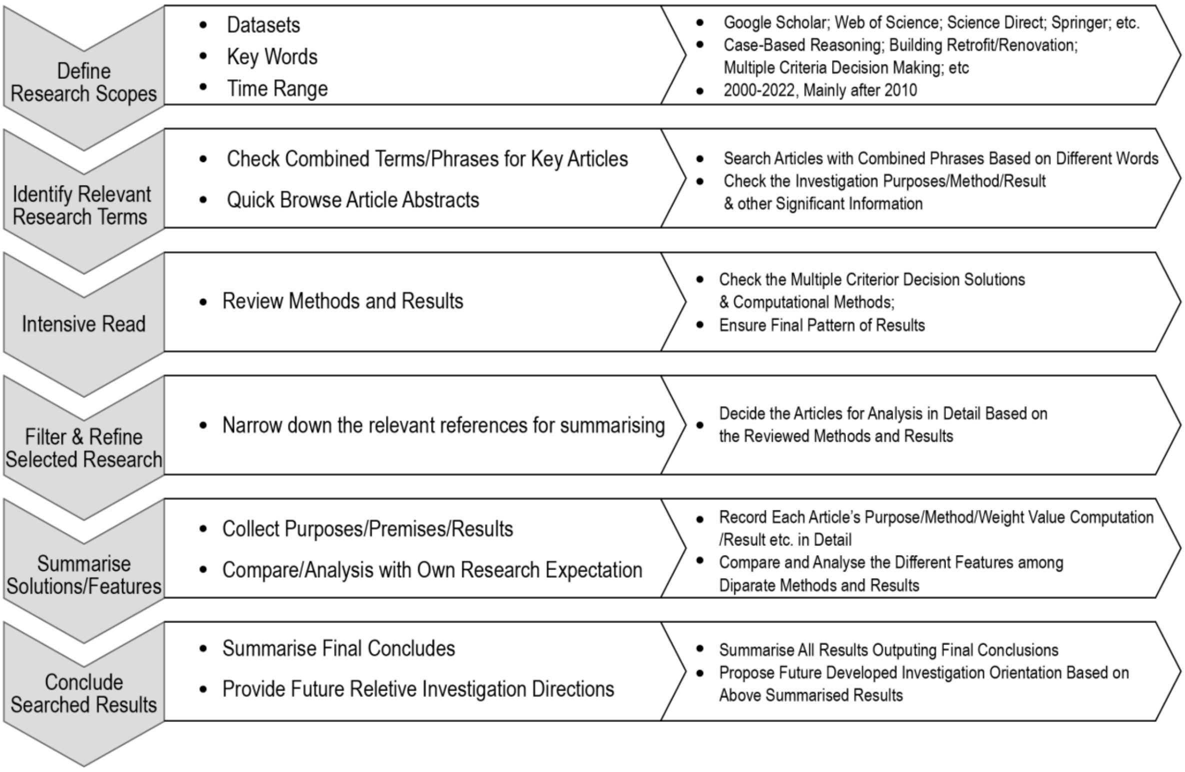


Figure 2 Investigation Workflow for Literature Review
[Image by Author]

It is essential to make the proper selection of literature resources. From Rivera et al.'s literature, they provided the suggestion for reliable digital library sources: Scopus, Web of Science, EI Compendex (Rivera, et al., 2022). Besides these 3 resources, the initial resource of relevant literature for this thesis is also mainly searched via Google Scholar, Science Direct, Springer, and the official website of H2020. In additional to those resources, government website are also used to research policy reports, such as (UK Climate Change Act 2008, 2009) from legislation.gov.uk., and English Housing Survey (Ministry of Housing, Communities & Local Government, 2016) that obtained from Gov.UK. When a relevant literature is found, a further exploration of its bibliography is conduct. In the first round of review, it is found that most of the literature related to thesis were mainly published after 2000. Apart from some literature for basic principle, such as the AHP was proposed by Saaty in 1994 (Saaty, 1994), this thesis's topic of modular retrofit, renewable energy technology and decision-making support are more developed after 2000.

Regarding the investigation purposes of reviewing the CBR method in building energy renewable retrofit, how to find the most match case is the core problem of the literature review based on the decision makers' demands. The keywords of literature research are divided into three categories: "Building Retrofit", "CBR" and "Decision-making Model". The words and phrases related to these 3 categories are selected as search clues. Such as 'building renovation/retrofit', 'multiple criteria decision making', 'decision-making support model', 'multi-objective', 'case-based reasoning building', etc. Those terms are used as keywords for finding references. Besides the main goal of reviewing "Case-based Reasoning", other well-known machine learning algorithms used for decision making, such as KNN, can be used as keywords as well to retrieve other research results that may relate to building retrofit for comparison.

A mass of publications and research reports, etc. were gathered in the first round of research. Filtering the irrelevant research is essential. Quick browsing the abstracts of each article and reports to select the relevant research for intensive read. In the intensive reading, a more precise narrow down shall be made based on the reviewed method, results, purposes, etc. Those filtered materials from the seconded round narrow down then could be further researched for detailed comparisons and analysis. During this intensive reading, more literature would be reviewed based on the references and bibliography from all the publications, as those provide a broader mind and useful case learning for further investigation.

It should be noted that all the above machine learning and decision-making methods are not always in the domain of architecture or building retrofit. But this type of solution can be used to analyse some architecture-related problems. Therefore, it is necessary to review these studies, which can also provide us with effective reference solutions and ideas. Although the literature covers a variety of methods in different fields of investigation, it is expected to select the most appropriate research in the field of building retrofit. The purpose of this study is to review relevant scholarly articles. By summarising the main reasons and specific solutions for each case study, it helps to find the most effective judgment method, study the significant gaps, and establish new contemporary methods with a systematic approach.

2.2.2 Case-Based Reasoning Approach

Case-Based Reasoning (CBR) was firstly developed by an American cognitive and learning scientist Janet Kolodner in 1992 (Kolodner, 1992). Leake (Leake, 1994) firstly successfully applied Case-Based Reasoning solution to coding couple years after. In Kolodner and Leake's point of view, CBR is considered as a learning loop of "remember, adapt and compare" (Finnie & Sun, 2003). The common perception of CBR is origin from Kolodner's principle of "4R"— "Retrieve", "Reuse", "Revise" and "Retain" (Kolodner, 1992). This 4R theory is widely accepted and applied into decision-making support. CBR is the central methodology in this research, which is why an in-depth literature review has been conducted to explore its applications and relevance to the field of modular retrofit. CBR is an artificial intelligence (AI) problem-solving technique that involves using past experiences or "cases" to solve new problems. In the context of modular building retrofitting, CBR enables the reuse of previous retrofit solutions to guide decision-making. At this step of "reuse", CBR is not creating a new solution. It only presents the most similar cases according to the demands. User will make the "Revise" based on the "Reuse" case and create a new solution. This new solution then can be "Retained" in the database.

The literature review on CBR delves into its fundamental principles, which revolve around the process of retrieving similar past cases, adapting their solutions to fit the current problem, and learning from the outcomes. This approach is particularly valuable in fields such as construction and building retrofit, where solutions are often context-specific, and each project presents a unique set of challenges. By identifying and comparing similar cases, CBR can provide actionable insights that streamline the decision-making process and reduce uncertainties.

To effectively apply the CBR method, it is necessary to discuss the statistic hybrid algorithm as the key component of the CBR system. By analysing the data and optimizing the algorithm, the accuracy and efficiency of case retrieval and decision adaptation can be improved. The statistic hybrid algorithm is a research hotspot every year. Shown in Figure 3**.** Since the statistic approach is a mature and applicable technology, which could be reformed easily forming new computational methods based on traditional statistical solutions. While questionnaire method indicates the smallest research as it is difficult to investigate the objective level and convenience.

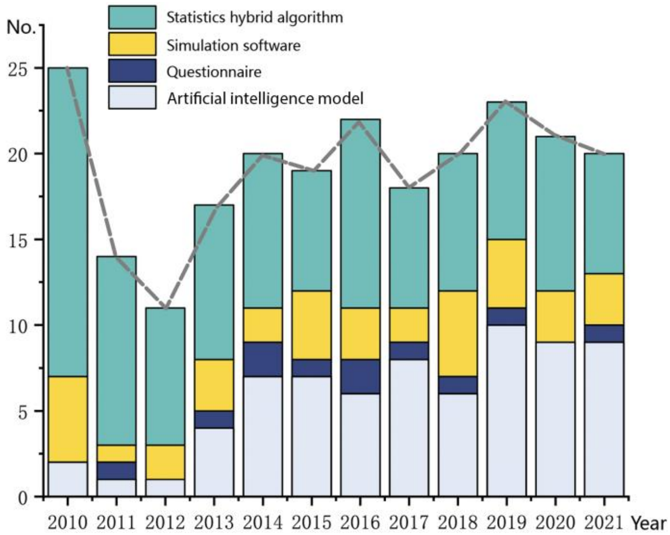


Figure 3. Research relevant to 4 different common ways used in decision-making
[Image by Author (Li, et al., 2024)]

In the aspect of artificial intelligence algorithms, especially in recent years, there is an obvious growth trend. This phenomenon shows that artificial intelligence algorithm is gradually applied to solve multi-criteria decision-making problems. This is due to significant developments in the field of artificial intelligence research, providing innovative solutions for machine learning.

Therefore, according to the current research status, AI technology will be more and more applied in the field of decision research. It is necessary to review the research of artificial intelligence algorithms. Among the artificial intelligent algorithms category, the proportion of research combined with CBR are gradually increasing over the past decade. Shown in Figure 4**.**

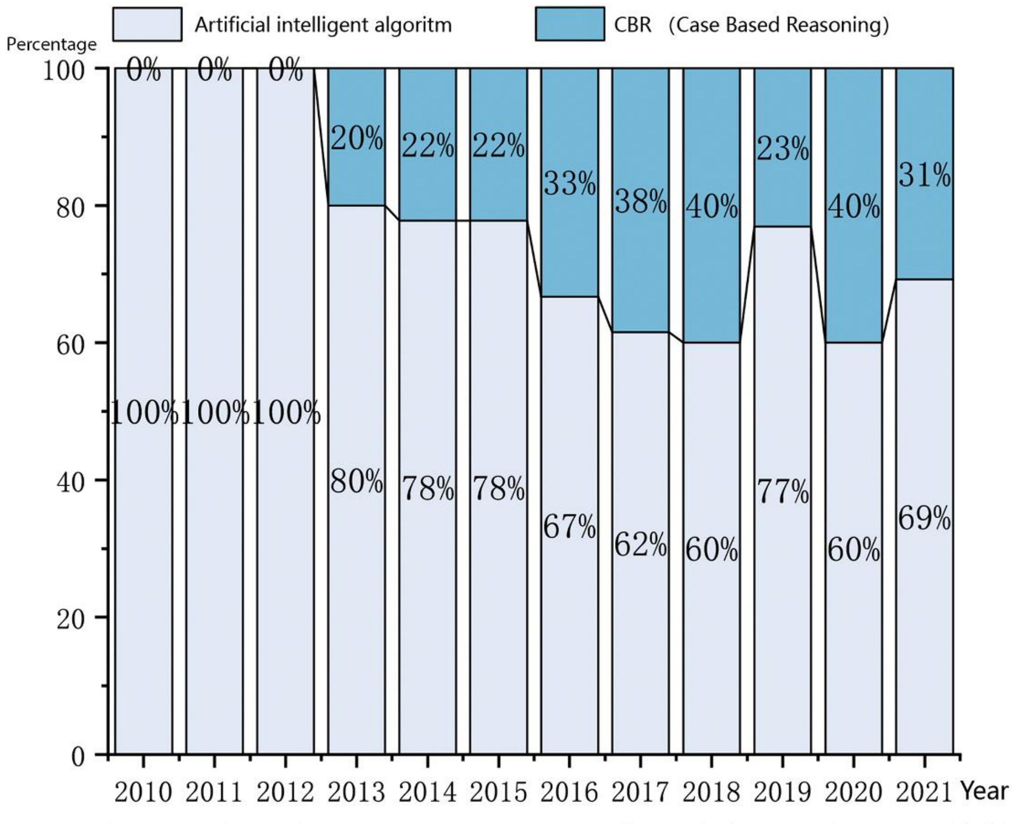


Figure 4 CBR investigations among AI algorithms for Building Retrofit
[Image by Author (Li, et al., 2024)]

In addition to exploring the basic principles, the review highlights various CBR applications in the construction industry, with a focus on energy efficiency retrofits. Studies demonstrate that CBR has been successfully used to inform decisions regarding building design, energy performance improvements, and material selection, particularly in scenarios where data is complex and varied. The literature also examines the integration of CBR with other decision-support tools, such as multi-criteria decision-making (MCDM) methods, to enhance its effectiveness in evaluating different retrofit strategies.

Moreover, the review investigates the key challenges associated with implementing CBR in building retrofitting. These include the need for comprehensive and accurate case databases, the difficulty of adapting solutions to new contexts, and the importance of ensuring that the retrieved cases are relevant and applicable to the current project. Despite these challenges, the literature suggests that CBR holds significant potential to improve the efficiency and effectiveness of modular retrofit projects, particularly when dealing with the complexities of integrating renewable energy technologies and optimizing building performance.

In summary, the Case-Based Reasoning approach is thoroughly examined in the literature review to underscore its importance and applicability to modular retrofitting. The insights gained from the review form the foundation for this research, demonstrating how CBR can be adapted and applied to support decision-making in the modular retrofit process.

2.3 Stage 2: Database Setup

2.3.1 Case Study for Prototype of CBR Model

The cases reviewed in this section is filtrated by the process of overview other relative literatures. This process experiences four phases and gradually narrowing down to the selected projects conforming to the subject of this section. These four phases are defined disparate keywords to search homologous datum. Finally, after scanning and checking all relative literatures, these projects and other information worth to be studied can be obtained. Following four phases are described in detail.

Phase 1: Search relative information in general. This phase refers to the preliminary step in the process of the literature search, allowing authors to collect several scientific works from the paper database such as Scopus, Science Direct and Google Scholar, fund projects from European commission and other countries' fund projects etc. The keywords in this step being used to identify building energy façade have been "urban energy consumption + façade/envelop", "building energy efficiency + façade/envelop", "building renovation/retrofit + façade/envelop" and "building energy performance + façade/envelop". As there are so much building energy consumption related literatures, the word 'façade/envelop' is added into key items aims to narrow down the scope of results.

Phase 2: After above overall searching, all literatures about building energy condition of façade have been achieved. However, according to some studies have been done, the building façade development of the energy efficiency of buildings has shown a growth because of the development of advanced techniques and methodologies in the last 2 decades. So, all these papers and reports are filtered in accordance with the year 2000 that means to pick up literatures published after 2000.

Phase 3: Via the second screening, whole datum mainly focuses on building façade research about energy saving aspect. However, this report mainly studies the retrofit façade under modular pattern. Therefore, the keywords ‘module’, ’modular’ should be added to choose papers and fund in further.

Phase 4: As this study focuses on specific constructions of building façade utilizing renewable energy sources of modular approach in the condition of Europe, so outcome shall be demonstrated or experimented on-site and employs the renewable energy sources such as solar energy. Under this circumstance, some projects in Horizon 2020 and articles are achieved. Indeed, eliminating the repetition section that refers to the papers funded by the Horizon 2020 projects; thus, those projects are picked up from Horizon 2020 in line with the requirement of modular building façade with energy efficiency utilizing renewable energy sources.

2.3.1.1 Review Cases

As described above, the projects from Horizon 2020 programme that use renewable energy sources, which are investigated in this research, (shown in Table 7). Since each project operates in different climate conditions, the construction logic and techniques vary for each case. To systematically review the projects, the analysis focuses on four aspects: construction, renewable energy types, features, and purpose. Construction is the most significant but also the most complex aspect to summarize. Based on the building envelope’s fundamental logic, this study uses a layered framework to analyse the construction. These layers provide a detailed view of the building façade structure, which architects can use to replicate the construction. It’s important to define the layers for each building type, as façade construction logic varies significantly. Therefore, the renewable energy type should be defined in advance to reduce the variety of layer patterns.

2.3.1.2 Categorizing Benchmarks

Renewable energy refers to non-fossil energy sources. In this study, it specifically refers to energy techniques integrated into building façades. Based on the Horizon 2020 project review, three main types of modular façade technology—ventilation, solar collectors, and photovoltaic (PV) panels—are commonly used.

- **Ventilation** involves building façades with air cavities that use airflow turbulence.

- **Solar collectors** are installed on the building envelope to absorb solar energy and generate heat for water or air.

- **PV panels** are integrated into façades to capture solar energy and generate electricity.

2.3.1.3 Summarising Constructions

The database analysis is based on the construction features of the 23 projects selected from Horizon 2020, shown in Table 7. The reasons for choosing these 23 projects for further review will be discussed in 5.1.1.1. To support this research, the constructions are summarized according to layers, organized by renewable energy type. This allows the building façade structure to be easily understood, especially by architects. Four layers are defined: exterior, core, facing, and support. The substrate layer is the basic structure (e.g., walls), while the exterior layer is the outermost part, exposed to the environment. The support layer connects the façade to the substrate, and the core layer functions to house renewable energy technologies such as ventilation or PV. All project constructions are summarized in a table, categorized by renewable energy type, to form the original database for algorithm analysis.

2.4 Stage 3: Tool Development

2.4.1 Prototype of CBR Decision-making Support

The 23 projects selected from Horizon 2020 (shown in Table 7) are distributed in different areas and include various types of buildings, such as offices, residential units, etc. The detailed analysis of those projects will be discussed in section 5.2--Case Study of Modular Retrofit with Renewable Energy Technologies. Based on the reviewed modular renovation projects, an Excel database (please see Appendix A) was created to track retrofitting module façade constructions for different projects. Since this research primarily focuses on modular renovation methods for existing buildings, the cases were detailing all layers of renovation construction patterns, locations, functions, substrates, and more. Each item is tagged with keywords for easy identification by the program. It's important to note that the items follow specific rules for classification, rather than being named according to the researchers' opinions. The frequency of each term is analysed to shape the construction model, and the relationships between items are also studied to explore their internal connectivity.

On this basis, it is necessary to bind the high-frequency combinations to effectively extract potentially valuable information. To achieve this, the Apriori algorithm, a classification method developed by Agrawal and Srikant in 1994 (Agrawal & Srikant, 1994), is introduced to identify and analyse high-frequency item sets and the association rules between them. This provides a theoretical foundation for the subsequent analysis and optimization of architectural models.

2.4.1.1 Application and Implementation of CBR

2.4.1.1.1 Apriori algorithm (Association algorithm)

Apriori is a frequent itemset mining and association rule learning algorithm based on relational databases (Agrawal & Srikant, 1994). It first identifies individual items that frequently occur in the database and extends them to increasingly large item sets, if these item sets appear frequently enough in the database.

Apriori is designed to operate databases containing transactions. Each transaction is regarded as a set of items (an itemset). As Dosh & Joshi indicated, Apriori employs a "bottom-up" approach (Dosh & Joshi, 2018), in which a frequent subset expands one item at a time and tests of the candidate groups based on the data.

La mentioned in his publication that the Apriori algorithm is mainly applied in fields such as retail market shopping basket analysis to find items that are frequently bought together (La, 2018).

2.4.1.1.2 Attributes Weighting--AHP Method for Subjective Weightings

The Analytic Hierarchy Process (AHP) was the algorithm first proposed by Saaty in the 1970s (Saaty, 1994). It is employed to derive subjective weightings for the evaluation attributes (Cui, et al., 2024). This process involves constructing pairwise comparison matrices to quantify the relative importance of attributes.

As Alonso & Lamata presented the AHP calculation process in their research, they set 2 itemset to represent the set of decision-makers, and the weight vector of each decision-maker (Alonso & Lamata, 2006). For simplicity and fairness, Alonso & Lamata assumed that all decision-makers contribute equally, this strategy of using hypothetical weighting ratio will be adopted for the demonstration of prototype in Chapter 5.

In the next step for AHP calculation, the decision matrix for each decision-maker contains the pairwise comparisons of n attributes. Each matrix is subjected to a consistency test to ensure reliability. The Consistency Index (CI) and Consistency Ratio (CR) are computed as follows (Alonso & Lamata, 2006):

$$C.I. = \frac{\lambda_{max} - n}{n - 1}$$

$$C.R. = \frac{C.I.}{R.I.}$$

Alonso & Lamata described here that λ_{max} represents the maximum eigenvalue of the matrix, and RI is the random index based on the size of the matrix (Alonso & Lamata, 2006). If $CI < 0.1$, the pairwise comparison matrix is deemed consistent.

After confirming consistency for all decision-makers, a final aggregated decision matrix is obtained by integrating individual matrices. The subjective weightings are then determined by computing the normalized eigenvector (Alonso & Lamata, 2006).

2.5 Stage 4: Verification

The verification of the Case-Based Reasoning (CBR) model integrated with the Analytic Hierarchy Process (AHP) follows a multi-stage protocol to ensure its technical robustness and practical validity. Given the hybrid nature of the tool—combining historical case adaptation (CBR) with multi-criteria prioritization (AHP)—the verification process addresses both algorithmic accuracy and decision-making relevance through the following potential ways:

1. **Expert Review and Consistency Checks**

   Structured expert interviews are conducted to validate the hierarchical criteria structure of the AHP component. Domain specialists (e.g., architects, energy engineers) evaluate the weighting of factors such as cost, energy savings, and technical feasibility, ensuring alignment with industry priorities. The consistency ratio (CR) of pairwise comparisons in AHP is calculated, with $CR < 0.1$ indicating acceptable logical coherence (Saaty, 2008). Discrepancies are resolved through iterative Delphi rounds until consensus is achieved.

2. **Sensitivity Analysis**

   The model's responsiveness to input variations is tested by perturbing key parameters. This identifies "decision boundaries", which are points where the model's output (like a ranking) abruptly changes, as Yu et al. mentioned in their research for the assessment of the parameter sensitivity (Yu, et al., 2023). It confirms that rankings remain stable within realistic uncertainty ranges.

3. **Cross-Validation with Alternative Methods**

   To mitigate overfitting, results are compared against outputs from standalone methods. In this study, a combination with TOPSIS is adopted for weighting, this algorithm is also studied in Dagdeviren et al. and Cui et al.'s research (Dagdeviren, et al., 2009; Cui, et al., 2024). Based on the results from the demonstration, evaluate whether the CBR-AHP hybrid significantly outperforms benchmarks in criteria such as solution relevance and computational efficiency.

4. **User Feedback in Pilot Scenarios**

   Practitioners apply the tool to ongoing retrofit projects, evaluating its usability and decision-support value through surveys.

According to this, the 3rd approach (Cross-Validation with Alternative Methods) offers a more objective and generalisable validation compared to other approaches. While expert reviews and user feedback risk subjective biases, and retrospective case testing or sensitivity analysis often require large datasets for reliable conclusions, cross-validation directly benchmarks the model's performance against established algorithms under unified criteria. This method quantifies robustness against overfitting, validates decision-making logic without dependency on human judgment or excessive historical data, and highlights the hybrid CBR-AHP model's unique strengths in balancing qualitative and quantitative factors—ensuring broader applicability across diverse retrofit scenarios.

2.6 Summary

This chapter outlines a four-stage methodological framework to address the research objectives. *Stage 1* involves a systematic review-- Chapters 3 (Literature Review) and 4 (CBR Approach) -- of retrofit practices, decision-making models, and modular design principles, which builds up the theoretical foundation. *Stage 2* focuses on database setup (Chapter 5), where historical retrofit cases are curated and analysed to define benchmarks for key attributes (e.g., energy savings, cost). This structured repository enables standardized case retrieval and comparison. *Stage 3* (Chapter 5) develops a CBR prototype, integrating algorithmic workflows (e.g., similarity calculations, AHP weighting) into a user interface for scenario testing. Finally, *Stage 4* (Discussed in Chapter 6) implements verification through cross-validation with alternative methods (TOPSIS), ensuring the model's robustness against subjective biases and data limitations. Collectively, this iterative methodology bridges theoretical insights with practical implementation, prioritising transparency, and adaptability across diverse retrofit contexts.

3 Literature Review

3.1 Introduction

The global imperative to decarbonize the built environment has positioned building retrofitting as a critical pathway to achieving energy conservation and emission reduction targets. Within this context, the United Kingdom's post-war housing stock—characterized by its standardized, mass-produced prefabricated construction—emerges as a high-priority candidate for scalable retrofitting solutions. These buildings were built rapidly to address post-war housing shortages, but now they are facing systemic inefficiencies due to outdated materials, poor thermal performance, and aging infrastructure. However, their inherent modularity and uniformity present unique opportunities for systematic, cost-effective upgrades.

This literature review chapter integrates interdisciplinary research to establish a foundational understanding of retrofitting challenges and innovations, structured across 5 thematic pillars:

First, it examines the distinctive attributes of post-war prefabricated housing in the UK in Section 3.2, highlighting their structural homogeneity and deterioration patterns that make them ideal for modular interventions.

Second, it explores the principles of modular design in Section 3.3, defining its role in retrofitting as a methodology that balances standardization with adaptability, enabling prefabricated component integration without compromising building functionality or heritage values.

Third, it synthesizes existing knowledge on building retrofit processes in Section 3.4, dissecting generic challenges such as fragmented workflows, stakeholder misalignment, and technical uncertainties across key phases—audit, design, implementation, and validation.

Fourth, it evaluates energy efficiency retrofit strategies in Section 3.5, emphasizing the importance of strategic planning, technology selection (e.g., passive vs. active systems—embedded renewable technologies), and performance modelling tools to optimize outcomes.

Finally, the review critiques multi-criteria decision-making approaches in Section 3.6, contrasting conventional methods (e.g., Analytic Hierarchy Process (AHP) with the emerging potential of Case-Based Reasoning (CBR)**.** While traditional multi-criteria decision-making frameworks often rely on static criteria weightings or abstract theoretical models, CBR introduces a dynamic, context-sensitive paradigm by leveraging historical retrofit data to inform real-time decision-making. This capability aligns seamlessly with the Design Research Methodology

(DRM) proposed in this thesis, which serves as the overarching framework to systematize modular retrofits across heterogeneous building stocks.

3.2 Target Building Type: Prefab Post-war Housing

3.2.1 Background and Definition

The aftermath of World War II exacerbated severe housing shortages and material scarcities across the United Kingdom, critically impacting both the quantity and quality of housing. To address this crisis, the UK government revived its post-World War I strategy of large-scale public housing investment. In 1942, Prime Minister Winston Churchill established the Burt Committee (officially the *Inter-Party Committee on Housing*), tasked with identifying rapid construction solutions.

The Committee's mandate focused on prefabricated housing, inspired by wartime innovations. In 1943, it dispatched engineers to the United States—a leader in wartime prefabrication—to evaluate modular construction techniques (Bullock, 2002). Their findings concluded that prefabricated buildings offered the most viable path to mass housing delivery, balancing speed, cost-efficiency, and material optimisation. The Burt Committee's final report in 1944 endorsed prefabrication as the cornerstone of post-war housing policy, leading to the Temporary Housing

Programme and the eventual construction of over 156,000 prefab units by 1951 (Blanchet & Zhuravlyova, 2018).

Prefabricated housing (Prefabs) formed the cornerstone of the UK's strategy to address post-World War II housing shortages. In March 1944, Prime Minister Winston Churchill's wartime coalition government enacted the Housing (Temporary Accommodation) Act, legislating a mass production program for prefabs. Informed by the 1942 Burt Committee (officially the *Inter-Party Committee on Housing*), which projected a post-war housing deficit of 200,000 units, the Act aimed to deliver 300,000 prefabricated homes within a decade, backed by a £150 million budget (Great Britain, 2007).

The program leveraged wartime factories and standardized designs to accelerate construction. By 1951, 156,623 prefabs had been built, surpassing initial targets and accounting for 13% of the 1.2 million new homes constructed between 1945–1951 (Blanchet & Zhuravlyova, 2018). Notably, many prefabs—originally designed for a mere 10-year lifespan—remain standing today, a testament to their durable construction methods, such as prefabricated reinforced concrete (PRC) (Town and Country Planning Association, 2018).

This initiative also spurred innovation in non-traditional building technologies. Local authorities adopted modular techniques to meet cost and speed demands, laying the groundwork for later systemic prefabrication in UK housing (Bullock, 2002).

3.2.2 Disadvantages and Retrofit Requirements

Post-war prefabricated houses in the UK, primarily designed as single-family dwellings of modest scale, exhibit systemic energy inefficiencies due to decades of material degradation and outdated construction standards. A case study of Tarran Newland prefab estates reveals recurring issues:

- Wall Construction: Walls comprise precast concrete slabs (20mm thickness) with bolted steel plates, creating severe thermal bridging. Gaps between fiberglass insulation and fibreboard further reduce thermal resistance, resulting in U-values exceeding 1.5 W/m^2K—far below modern standards of 0.3 W/m^2K (House Energy, 2022).
- Roof Design: Shallow roof pitches (typically 15°) hinder insulation installation, limiting loft insulation to <100mm thickness (Harrison, 2020).
- Air Permeability: Measured air leakage rates average 19.26 $m^3/(h \cdot m^2)$ in Tarran Newland units, nearly double the Part L Building Regulations limit of 10 $m^3/(h \cdot m^2)$ and six times the sustainable housing benchmark of <3 $m^3/(h \cdot m^2)$ (Ultimate Coatings LTD., 2023).

These deficiencies—thin walls, inadequate insulation, and excessive air leakage—force residents to allocate 25% of household income to energy costs, compared to the UK average of 8% (National Energy Action, 2022). The dwelling stock in England is heavily concentrated in buildings constructed between 1945 and

1980. This age distribution highlights a significant opportunity for energy efficiency retrofits, as structures from this period are predominantly characterized by outdated insulation, single-glazed windows, and inefficient heating systems. Prioritizing these buildings aligns with the UK's Net Zero Strategy, which identifies retrofits as critical to achieving a 40% emissions reduction and a combine of around 32% for both renewable energy and energy efficiency in retrofit by 2035 (HM Government, 2021). Consequently, this data underscores the urgent need for large-scale, modular retrofit strategies tailored to the UK's aging prefab housing stock.

3.2.3 Reasons for Selecting Prefab House

Despite being over half a century old, the enduring preservation of post-war prefab houses in the UK demonstrates the long-term durability of their original design and construction methods. While these structures no longer comply with modern building standards—particularly in thermal performance and airtightness—their proven resilience underscores their potential for adaptive reuse through retrofitting. This section outlines three key rationales for selecting prefab housing as a retrofit priority:

1. Modular Design Compatibility:

   These Prefab houses have a significant characteristic of modular which represents that the building façade could be installed and manufactured in module pattern. Those prefab houses are often constructed in standardised production and assembly of building facades through industrialised manufacturing processes, which precisely match the concept of attaching envelopes outside of the existing façade. Technical components, such as solar collectors and photovoltaic panels, etc., can be embedded in modules to enable the attaching envelops to achieve the goal of energy efficiency. This feature conforms to the target of this investigation of using building renewable energy technique in modular solution.

2. Scalability of Solutions

   Originally conceived for mass production to address post-war housing shortages, prefab estates were designed for rapid replication—a principle that remains relevant for large-scale retrofitting. Retrofitting these homes can leverage existing supply chains and standardized designs, reducing costs by 20–30% compared to bespoke renovations (NHBC Foundation, 2022). This scalability supports nationwide decarbonization goals, such as the UK's target to retrofit 1.5 million homes annually by 2030 (Climate Change Committee, 2019).

3. Proven Structural Integrity with Energy Efficiency Deficits

   While prefab buildings exhibit robust structural performance, their energy inefficiencies result in disproportionately high heating costs. Retrofitting these homes could reduce energy consumption by 40–60%**,** translating to annual savings of £800–£1,200 per household (National Energy Action, 2022).

3.2.4 *Representative Prefab House Types*

When the Ministry of Industry opened the design competition, there were approximately 1,400 designs submitted. During the review, many projects were rejected at the concept stage, such as British Powerboat Company's proposal for the Jicwood all laminated plywood design (Goodman & Chant, 1999), while other projects were rejected after the prototype stage, such as the steel framed Riley (Blanchet & Sonia, 2018). Eventually, some were approved for construction after testing. Some representative cases are denoted as follows:

- AIROH (THP)

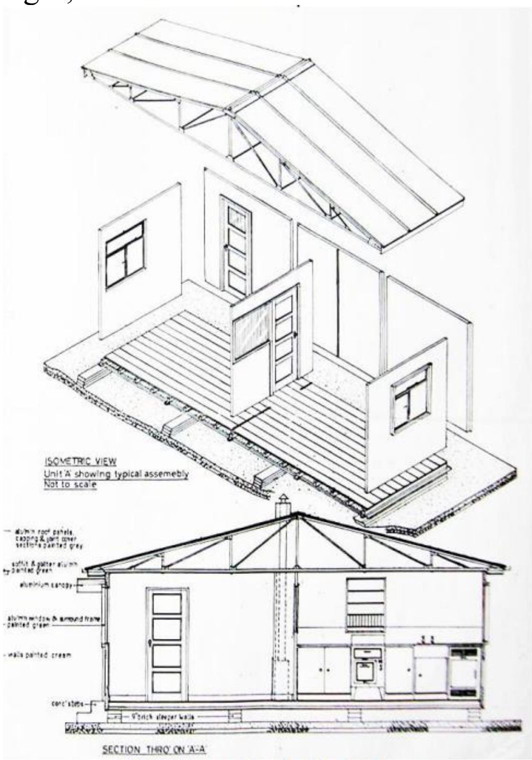
The AIROH (Aircraft Industrial Housing Research Organization) house (Figure 5) exemplified post-war Britain's industrial ingenuity, delivering a lightweight, fully prefabricated aluminium bungalow designed for rapid mass production. Key features included:

- **Modular Design**: Each 675 sq. ft (62.7 m²) unit comprised four factory-finished sections, transported by truck and assembled on-site, complete with furnishings such as curtains and fixtures (Penrose, 2010).
- **Unprecedented Speed**: Leveraging aircraft manufacturing techniques, AIROH houses required only around 2,000 prefabricated components (versus

20,000 for a wartime aircraft), enabling assembly of a complete dwelling every 12 minutes on production lines (Bullock, 2002).

- **Cost Efficiency**: By 1947, each unit cost £1,610 (equivalent to ~£65,000 today), excluding land and installation, with 54,500 units produced nationwide to address housing shortages (Davis, 2005; Blanchet & Zhuravlyova, 2018).

Despite its innovative design, the AIROH's all-aluminium construction posed long-term durability challenges, as corrosion and thermal inefficiencies led to



AIROH bungalow basic structure.

eventual replacements by sturdier concrete prefabs. Nevertheless, its legacy persists as a milestone in modular construction history. Typical structure shown in Figure 5.

Figure 5 AIROH basic structure and installation
[From: https://medium.com/@briancpotter/englands-aluminum-houses-the-airoh-house-2d029a6a6bb6]

- BISF (Permanent House)

In Figure 6, the BISF (British Iron and Steel Federation) house, introduced in 1946, exemplifies post-war Britain's innovative use of steel in mass-produced residential architecture. Designed by the British Iron and Steel Federation, its structural and material composition includes:

- Structural Framework:
    - Primary Load-Bearing System: A steel column-and-beam skeleton forms the main structure, with standard Crittall Hope steel windows integrated between columns.
    - Central Spine: Steel pipe columns support first-floor beams, creating an open-plan layout typical of post-war prefabs.
- Cladding System:
    - Lower Exterior: Vertical steel cladding or optional brick veneer for aesthetic flexibility.
    - Upper Exterior: Corrugated steel sheets fixed to steel angles, often paired with timber windboards for weatherproofing.
    - Roof: Steel truss panels with shallow pitches, originally clad in asbestos cement sheets (later replaced with modern alternatives).
- Internal Construction:

- Partitions: Timber-framed walls lined with plasterboard or compressed fibreboard.
- Flooring: Tongue-and-groove timber boards on steel joists.
- Ceiling: Plasterboard or fibreboard panels separated from exterior walls by glass wool quilting for rudimentary thermal insulation.

- Design Features:
  - Protruding Crittall Hope windows to maximize natural light.
  - Modular assembly enabling rapid on-site construction, with standardized components reducing costs by 30% compared to traditional builds (Cooper, 2015).

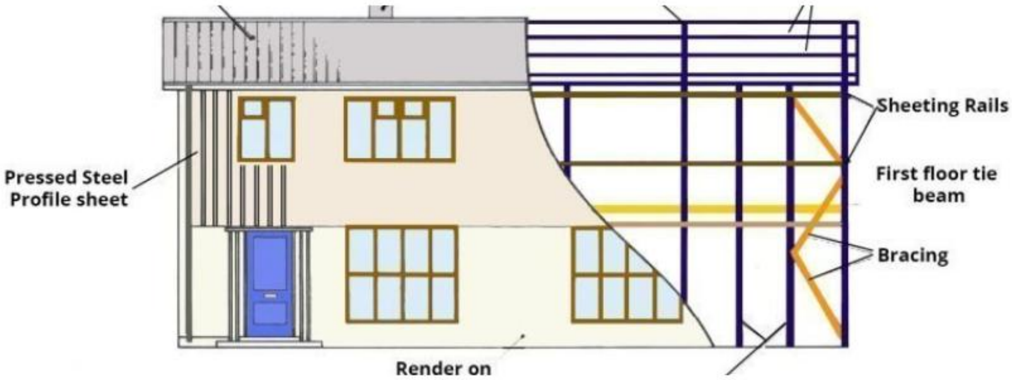


Figure 6 BISF Houses
[From: https://nonstandardhouse.com/what-the-bre-said-about-bisf-houses/]

- Laing "Easiform"

Laing & Co.'s pioneering in-situ concrete housing systems, developed from 1919 onward, revolutionized mass housing construction by avoiding the material shortages and complexities of steel-frame methods. Shown in Figure 7 Laing "Easiform" . Three distinct iterations emerged:

1. Mk1 (1919–1928):
   - Wall Construction: 8-inch (20 cm) monolithic walls using clinker concrete (a low-carbon mix of sintered coal ash and cement), notable for its durability and minimal efflorescence ("powder-free") (Cooper, 2015).
2. Mk2 (1925–1945):
   - Composite Walls: 3-inch (7.6 cm) inner leaf + 2-inch (5.1 cm) outer leaf, cast in-situ using timber formwork. (HI Resources, 2010)
   - Exterior Finish: Pebble-dash render (a period-appropriate "stone dotted" coating) for weather resistance.
3. Mk3 (1945–):
   - Enhanced Specification: 3-inch inner/outer leaves separated by a 2-inch cavity for rudimentary thermal insulation.

- Post-War Adoption: Became Laing’s standard post-WWII system, deployed in 70% of their 1945–1955 housing projects (Bullock, 2002).

Figure 7 Laing "Easiform" Housing
[From: https://www.permarock.com/project-spotlight/laing-easiform-non-traditional-housing-grantham]

- Mowlem

The Mowlem in-situ concrete system, akin to the Laing Easi-Form method, emerged as a post-war construction innovation, first deployed in 1952 and widely adopted between 1962 and 1981 (Kivlehan, 2022). This system utilized cast-in-place lightweight concrete to replace traditional masonry, prioritizing speed, and structural efficiency. As shown in Figure 8. Key design features include:

1. Solid Wall Construction:
    - 225 mm (8.9 in) thick monolithic walls made of lightweight aggregate concrete (e.g., expanded clay or shale), offering improved thermal performance (U-value: ~1.2 W/m²K) compared to dense concrete (Sassine, et al., 2021).

- Exterior finishes such as textured render or pebbledash for weather resistance and aesthetic appeal.

2. Cavity Wall Adaptation:

    - 100–125 mm (3.9–4.9 in) thick inner leaves of reinforced concrete, paired with external cladding to enhance insulation and moisture management (Ghosh, 2024).
    - Cavity gaps (50–75 mm) occasionally filled with mineral wool in later retrofits to meet evolving energy standards. (HI Resources, 2010)

Technical Advantages**:**

- Speed of Construction: Eliminated bricklaying delays, reducing on-site labour by 40% (Rocha, et al., 2023).
- Material Efficiency: Lightweight concrete reduced foundation loads, enabling cost savings in high-density housing projects.

Figure 8 Mowlem projects house graph

[From: https://flettons.com/the-mowlem-house-a-comprehensive-guide-for-home-buyers-and-investors/]

- Wimpey "no fines"

Wimpey no-housing is a construction method and a series of housing designs produced by George Wimpey Company. It aims to produce social housing for families on a large scale. It was developed by the Ministry of Construction under the emergency factory manufacturing program after World War II.

The Wimpey No-Fines system, developed by George Wimpey & Co. under the UK government's post-World War II Emergency Factory Made Housing Program, revolutionized social housing construction through its innovative use of fine-free concrete. "Fine-free" refers to the type of concrete used-concrete without fine aggregate. (Buildings Research Establishment-BR153, 1989) This material—composed solely of coarse aggregate (gravel), cement, and water, with no fine sand—enabled rapid, cost-effective production of family homes at scale. Key features include:

1. Construction Method:
    - Monolithic Walls: Cast in-situ using reusable timber formwork, with wall thicknesses ranging from 225–300 mm (8.9–11.8 in) (Buildings Research Establishment-BR153, 1989).
2. Design Standardisation:
    - Semi-detached and terraced house templates with 2–3 bedrooms, standardised layouts, and pebbledash rendered exteriors.

- Over 300,000 units built between 1945–1955, primarily for local authority housing (Cooper, 2015).

3. Material Limitations:
   - Durability Issues: Susceptibility to water penetration and carbonation-induced reinforcement corrosion led to widespread dampness and structural decay by the 1980s (Ghosh, 2024).
   - Thermal Bridging: Lack of cavity insulation exacerbated heat loss, necessitating costly retrofits in later decades (Glew, et al., 2021).

Despite its decline, the No-Fines system (Figure 9) remains a landmark in post-war industrialized housing, exemplifying the trade-offs between speed, affordability, and long-term performance.

Figure 9 Wimpey "no fines"
[From: https://www.finance-hub.co.uk/wimpey-no-fines-construction]

3.3 Modular Design

3.3.1 Definition of Module/Modularity/Modularisation

Modularisation stands as a cost-effective strategy to enhance industrial efficiency by harmonising the benefits of standardisation and customisation. This concept, rooted in the Industrial Revolution, gained momentum with Henry Ford's pioneering standardization techniques in automobile manufacturing, which enabled mass production through interchangeable components (Ford, 2020). Standardisation laid the groundwork for configuring diverse products using shared, uniform parts.

The formal concept of modularization emerged later, drawing inspiration from the Bauhaus movement of the 1920s–1930s, which introduced modular "building blocks" to merge artistic design with industrial production (Winton, 2007). Bauhaus principles emphasised functional, adaptable units that could be combined creatively, laying the foundation for modern modularity. By the 1960s, this evolved into a structured approach where *modules*—distinct from basic building units—were defined as self-contained components with specific functionalities, capable of independent testing and integration. For instance, a laptop's display module not only serves a unique purpose but can also be validated separately before assembly.

Modularity is thus characterized by two facets (Miguel, 2005):

1. **System Attributes**: The interplay between a module's inherent functionality and its role within a larger system.
2. **Production Integration**: The seamless incorporation of standardized modules into manufacturing processes.

Nowadays, standardisation and modularity are pivotal to mass production, enabling flexible platforms where products are assembled from interchangeable modules. This approach reduces complexity while fostering diversity through three key drivers (Wang, et al., 2014; Zhao, et al., 2022):

1. **Diversification**: Customizing products by reconfiguring modules.
2. **Similarity Utilization**: Maximizing shared components to cut costs.
3. **Complexity Reduction**: Simplifying design and assembly via modular decomposition.

In practice, modularization streamlines complex systems by breaking them into manageable sub-units. This empowers designers to mix and match components, accelerating development and enabling tailored solutions for niche markets. For example, automotive manufacturers use modular platforms to produce electric and combustion-engine vehicles simultaneously, optimizing R&D investments (Ulrich, et al., 2020).

3.3.2 Development of Modular Design in Different Sectors

3.3.2.1 Vehicles

The use of a standard module across different products is known as a platform. The flexibility of a platform is widely used in vehicle manufacturing. By using the same modules, manufacturers can accommodate a small number of differentiated components and make minor adjustments to develop a limited range of products. For example, the suspension system can be used in different vehicles with only a few adjustments (Jose & Tollenaere, 2005). The concept of "platform" is like using a common manufacturing process, technology, and knowledge that is shared by multiple products in a series (Zha & Sriram, 2006). Therefore, the decision of which modules and assets should be unique or standardized in the product depends on cost analysis.

In vehicle production lines, common modules allow for the organization of standard manufacturing operations at the beginning, which can later be integrated with differentiated manufacturing operations for different product series. This process is known as "Postponement" (Jose & Tollenaere, 2005). The first differential manufacturing operation that occurs on the production line is called the "Point of Differentiation" (Jose & Tollenaere, 2005). Most industries aim to maximize the use of common components in their product lines because fewer differentiation operations lead to higher standardization demand. In this context, selecting the point of differentiation for platforms requires considering the balance between common modules and customized modules.

The key question is whether modularization should focus more on the optimization and customization of products with precise elements or on improving the standardization of modular products to meet mass needs. Developing a diverse range of modules could result in a wider variety of product choices, but it simultaneously increases economic and time costs. On the other hand, maximizing standardization and common modules could face challenges in addressing practical needs. Striking a balance between product variety and standardization is essential for industries to make informed trade-offs.

3.3.2.2 Computer & Mobile Devices

Compared to vehicle production lines, the product line for computers—or, more generally, mobile devices—is relatively more customized. Like vehicles, mobile devices have a certain number of base components and a series of assembly requirements. However, mobile devices allow for more flexible and independent selection of elements.

For instance, a modular smartphone consists of different base components, each with its own rate of change. Components such as batteries or screens are attached to the main board and can be installed or replaced independently in a modular design. These components are easy to install and remove without the need to rework the soldering. This not only reduces waste and costs but also improves user comfort by allowing customization based on customer needs.

Modular design can be critical for extending the life of products with short life cycles. The latest product developments and evaluations are increasingly aligned with environmental standards, including factors like life cycle, durability, upgradability, reparability, and recovery. While modular design supports some diversity, it is not necessarily the most sustainable option. Promoting diversity leads to higher consumption of materials and more complex product lines, as additional common connectors are required. Moreover, a greater total product capacity is needed to accommodate the maximum selection options and future technology upgrades.

3.3.2.3 Furniture

Although Thomas D. Miller defined a module as a unit that contains functionality (Miller & Elgård, 1998), in many fields, it is better to consider a module as having a structural meaning as well, rather than focusing solely on its functionality. In building blocks, the design of connections and modular connectors is responsible for structural functionality, in addition to the final construction. For example, Lego units or the Sun Mao units from ancient Chinese construction—each of these modular units plays a role in the overall structure. Furthermore, in modular design for structural connectors, standardized interfaces are designed for the composition of structures.

3.3.3 Modular Design in Architecture

Over the past decade, modular architecture has become established in many areas of the construction industry. In the past, modular architecture was primarily developed for temporary buildings due to its ease of manufacturing and installation. However, with advancements in prefabrication technology, the concept of using volumetric units is now widely applied in various building types. Prefabricated modules can integrate with energy-efficient technologies as part of a sustainable strategy.

The utilization of modularity in building construction can be considered from two perspectives: process modularity and product modularity. Process modularity refers to the simulation and demonstration of the building construction process. Common approaches include BIM-based Iterative Design Methodology (IDM), exchanging information with building performance simulation models (BPSM), advanced geometric techniques (e.g., 3D printing), and other tools and methodologies to evaluate the effectiveness of renovation solutions (D'Oca, et al., 2018). The adaptation of modular and repetitive design principles is carefully planned to minimize costs, speed up the construction process, and establish a spatial and visual language for the building design.

On the other hand, product modularity typically refers to the physical prefabricated components that expedite on-site construction. This can be divided into three types (Friedman, 2020) based on the degree of present modules:

- Slot Modularity: In this type, the interfaces between components are different, making it difficult to interchange components easily.
- Sectional Modularity: Components are connected through identical interfaces. An example of this is the integration of active systems for production from renewable energy sources (RES) or bioclimatic passive solar collectors (D'Oca, et al., 2018).
- Bus Modularity: A single component (the "bus") connects various components. In most cases, these components are supported by systems such as ventilation, integrated batteries, structures, materials, or other functions.

Modular architecture involves arranging functional elements into a structural module and developing both the functional and physical elements that can be defined within the interface specifications between components or modules. These efforts consider a module to offer one or a set of functions to the product.

Modular construction represents a transformative off-site building method, defined by the assembly of prefabricated volumetric modules that serve dual roles as structural units and spatial enclosures (Zhang & Wei, 2020). These modules are manufactured in controlled factory environments, enabling superior structural integrity, accelerated construction timelines (30–50% faster than conventional methods), and enhanced energy efficiency through precision engineering (Kamali & Kasun, 2016).

The building envelope in modular architecture is particularly critical, functioning simultaneously as the primary load-bearing system and the aesthetic interface. Pioneering innovations include:

- Brown's 1974 Patent: Introduced a modular facade system with sectionalized, interlocking roof components (Du, et al., 2019).
- Hövel's Openable Facade (2008)**:** Developed at Delft University of Technology, this metal-glass facade system enabled reconfigurable modular panels for adaptive reuse (Hövels, 2008).

Such advancements underscore the envelope's role in balancing modular standardization with site-specific performance demands.

3.4 Existing Building Retrofit Overview

3.4.1 Key Phases in a Building Retrofit Program

A structured building retrofit program typically follows five critical phases (Ma, et al., 2012; Luther & Rajagopalan , 2014) to balance energy efficiency gains, cost-effectiveness, and occupant satisfaction. These phases ensure systematic planning, execution, and validation of retrofit measures.

1. **Project Initiation & Pre-Retrofit Assessment**

   This phase defines the retrofit scope, objectives, and constraints (e.g., budget, timeline). Building owners collaborate with Energy Service Companies (ESCOs) to conduct preliminary surveys, identifying operational inefficiencies (e.g., air leakage, outdated HVAC) and occupant concerns. (Ma, et al., 2012; Luther & Rajagopalan , 2014)

2. **Energy Audit & Diagnostics**

   A detailed energy audit benchmarks the building's energy use intensity (EUI) against industry standards and identifies no-/low-cost energy conservation measures (ECMs), such as optimizing HVAC schedules or sealing ducts. Diagnostics leverage submetering and performance rating systems (e.g., LEED, BREEAM) to assess equipment efficiency and control failures. (Ma, et al., 2012; Ho, et al., 2021)

3. **Retrofit Strategy Development**

   Using energy modelling tools (e.g., Energy Plus) to simulate retrofit impacts. Multi-criteria decision matrices weigh factors like energy savings, occupant disruption, and regulatory compliance. (Ma, et al., 2012; Ho, et al., 2021)

4. **Implementation & Commissioning**

   Selected ECMs are executed using modular techniques (e.g., prefabricated façades). Real-time BIM updates track compliance with design specifications. (Ho, et al., 2021; RISE, 2024)

5. **Post-Retrofit Verification & Feedback**

   Post-occupancy evaluations often reveal a performance gap due to behavioural factors, informing long-term maintenance strategies. (Ho, et al., 2021; RISE, 2024)

3.4.2 Generic Building Retrofit Problem

The generic building retrofit problem involves systematically identifying, prioritizing, and implementing cost-effective energy efficiency measures within operational constraints—such as budget limitations, occupant displacement risks, and technical feasibility—to achieve optimal energy savings while maintaining indoor environmental quality (IEQ) and occupant comfort (Ma, et al., 2012). In the research by Ma et al., they proposed the key challenges for building retrofit include:

1. **Technology Selection**: Balancing upfront costs against lifecycle savings.
2. **Operational Trade-offs**: Minimizing disruptions to building occupancy during retrofits.
3. **Performance Uncertainty**: Variability in post-retrofit outcomes due to occupant behaviour.

Current approaches often unable to address these interdependencies holistically. For instance, while passive measures (e.g., envelope insulation) reduce heating demand by 30–60%, they may inadvertently worsen summer overheating risks without active cooling integration (Pérez-Lombard, 2020). This emphasizes the necessity of adopting systematic approaches such as the Design Research Methodology (DRM), which effectively resolves conflicts between different goals by embedding multi-criteria optimization and stakeholder engagement mechanisms. Among them, the modular strategy significantly reduces the renovation cost and construction period by using prefabricated components, while active stakeholder participation - such as through joint design workshops - helps to enhance the compliance and acceptance of the solution. By integrating data-driven decision-making, modular innovation and user-centred design, this phased implementation strategy has successfully transformed old buildings into high-performance assets, thus providing a feasible path for promoting global decarbonization goals.

3.5 Energy Efficiency Retrofit

Energy-efficient retrofit refers to the process of upgrading an existing building or system to enhance its energy efficiency and reduce energy consumption. It involves implementing various measures and technologies to optimize energy performance, lower greenhouse gas emissions, and reduce operating costs.

Some common measures that can be applied to buildings (Zhou, et al., 2016; Pombo, et al., 2016; Refnier, et al., 2022; Oliveria, et al., 2024; Alexakis, et al., 2025; Aloshan, 2025):

• **Insulation**: Improving insulation in walls, roofs, and floors helps to reduce heat transfer and enhance thermal performance, thereby decreasing the need for heating and cooling.

• **Energy-efficient windows**: Upgrading to windows with double or triple glazing, low-emissivity coatings, and insulated frames can significantly reduce heat loss or gain and improve indoor comfort.

• **Lighting upgrades**: Replacing traditional incandescent bulbs with energy-efficient LED lighting can result in substantial energy savings. Installing occupancy sensors and daylight controls further optimizes lighting usage.

• **HVAC system improvements**: Upgrading heating, ventilation, and air conditioning (HVAC) systems can lead to significant energy savings. This may include replacing outdated equipment with high-efficiency models, installing variable speed drives, and implementing smart controls for better system performance.

• **Energy management systems**: Installing energy management systems allows for better monitoring, control, and optimization of energy use within a building. These systems provide insights into energy consumption patterns, enable remote control of equipment, and help identify areas for further efficiency improvements.

• **Renewable energy integration**: Incorporating renewable energy sources, such as solar panels or wind turbines, can offset a building's energy demand and reduce reliance on fossil fuels.

• **Water-saving measures**: Retrofitting plumbing fixtures with low-flow faucets, showerheads, and toilets can significantly reduce water consumption and associated energy use for water heating.

• **Building automation**: Implementing building automation systems can optimize energy consumption by integrating various systems like lighting, HVAC, and occupancy control, enabling coordinated operation and energy-saving strategies.

• **Behaviour changes programs**: Educating occupants about energy-saving practices and encouraging behaviour changes—such as turning off lights and equipment when not in use—can contribute to energy efficiency improvements.

3.5.1 Model-Based Approach

3.5.1.1 Energy Simulation Models

Data-driven modelling creates computational models from raw historical data. When the underlying physical processes are unknown or traditional equations are overly complex, machine learning and statistical techniques are used to discover the relationships between input and output variables. In Ali et al.'s research, they categorised the data-driven modelling into 3 types (Ali, et al., 2023):

- White-Box Models: Full physics-based modelling that offering high precision but requiring significant computational resources, often used after a comprehensive scheme is determined. In architectural field, tools such as EnergyPlus**,** TRNSYS, and IESVE employ physics-based modelling to calculate hourly energy consumption by integrating parameters like envelope thermal transfer, HVAC system performance, and climatic data. For instance, in Royapoor et. al's research, they used EnergyPlus model with historical data to achieve high accuracy, in their report, the error margins like ±5% for Mean Bias Error (MBE) and below 10% for CV(RMSE) (Royapoor & Roskilly, 2015).
- Grey-Box Models: Combine data with partial physical equations (e.g., RC thermal networks), enabling rapid diagnostics for existing buildings, with parameter identification time reduced by 60% compared to white-box models.
- Black-Box Models: Rely solely on input-output data without physical principles (e.g., neural networks, random forests), ideal for nonlinear systems (e.g., district cooling load prediction).

3.5.2 Model-Free Approach

3.5.2.1 Expert Systems

Expert systems operate on the principle of mimicking human expertise through structured knowledge representations, utilizing rule-bases (e.g., IF-THEN logic derived from ASHRAE Guideline 36) and knowledge-bases (e.g., historical retrofit cases) to automate decision-making process, such as recommending HVAC control strategies. An example is the application of Fault Detection and Diagnosis (FDD), it is a real-time sensor data analysis against predefined rules identifies anomalies (e.g., refrigerant leaks) with up to 90% accuracy. (Zhou, et al., 2009) However, these systems face limitations including dependence on manual rule extraction, difficulties in handling high-dimensional uncertainties (e.g., extreme weather events), and a need for integration with machine learning for adaptive learning.

A comparison of Model-based and Model-free approach is shown in Table 1.

Table 1 Comparison for Model-based and Model-free Approach

Approach	Strengths	Limitations	Typical Use Cases
Model-Based	High accuracy, interpretability	Computationally intensive, data-hungry	New building design, policy scenarios
Model-Free	Real-time operation, transparency	Rule maintenance costs, weak generalization	Rapid diagnostics, operational management

3.5.3 Modular Retrofit

Modular retrofit involves prefabricating building components or complete units in a factory (Kim, 2025), and then installing them onto an existing structure to improve its performance. The novel modular system can integrate different functions such as electrical system, shading system, ventilation system, and renewable energy system (e.g., solar hot water, solar photovoltaics etc.) etc. into a wholeness unit toolbox, which achieves different side functions, simultaneously. This performance greatly simplifies the difficulty of the energy efficiency technique utilization and the corresponding volume of accommodating technologies.

Not only in this aspect, but the modular construction also has advantage on installation field. Traditional building renovation process requires various components of retrofitting to be manufactured in factory and then assembled on site. While the entire course of modular system fabrication could be assembled in advance and only need to be installed under wholeness condition on-site with special lift equipment. Under this circumstance, the on-site measurement simply demands fewer workers to mount modules directly on the wall employing some instrument (Du, et al., 2019). This method apparently saves manpower and other homologous devices comparing to traditional building retrofitting manner.

However, as for weakness, modular units may require a higher price than traditional renovation construction because the developed integration feature which requires excellent technique level. During the assembly period, despite this advanced system needs fewer workers with comparison to original retrofit plan, each staff must request a higher level of professionalism. This leads to augment of labour cost and be also hard to employ person (Du, et al., 2019).

As the skin of architecture, building envelope has significant impact on indoor environment. The heating and cooling demand of a building can be reduced through retrofitting building fabric and the use of other advanced technologies such as air tightness, windows shading, etc (Ma, et al., 2012). Traditional architectural renovation in terms of building envelope mainly focuses on single side of energy saving such as increase thermal insulation or employ solar shading. This efficiency of this type of mode is not high and the relative components are complicated. In contrast, modular building façade system is an innovative renovation solution, which integrates multiple energy conservation, approaches into one unit including energy supply and prevention sides. In this way, the architecture fabric could meet several requirements for energy saving methods simultaneously. For instance, innovative façade combined solar shading panel with insulation material could satisfy the energy supply and heating reduction demand (Vanaga, et al., 2023). However, this advanced innovative technique leads to other issues yet. As the result of the integration of multi-functions, the design and manufacture complication degree enhance apparently leading to architect consider more technical responsibilities. Meanwhile, the requirement of construction accuracy for the whole system is also greatly increased because that a single unit equips various multifaceted roles, which asks for exclusive count situation (Du, et al., 2019).

Renewable energy recently has increasingly arisen the interest of research community in past years. Orthodox construction commonly adopts thermal insulation manner such as increasing insulation layer thickness or just uses one sort of renewable energy such as solar photovoltaic. Moreover, the modular façade unit corporates different energy sources utilization technologies, for example, combining PV panel and thermal collector into box so that generating power and heat water simultaneously. The use of renewable energy technologies may also bring more benefits for commercial office buildings where a utility rate structure includes time-of-use differentiated electricity prices and demand charge is applied. Nevertheless, this innovative renewable energy integration technology brings about some contradictory difficult points. Diverse renewable energy sources may have paradoxical requirements regarding construction, position etc. For example, setting ventilated air cavity under the thermal collector contributes to decrease the temperature and then improve the solar panel efficiency. (Mirzaei, et al., 2014; Li, et al., 2024) However, too thickness of air chamber would impair the insulation capacity of building envelope (Bhamare, et al., 2023; Dahal & Krarti, 2025). Thus, how to dispose this incompatible problem is another challenge for designers. In general, modular façade system has more advantages than conventional building envelope renovation solution. This topic deserves more research in the future.

In Du et al.'s research, they summarized the structure of modular system into 3 categories: Layer-based, Frame-based, Combination of Frame and Layer-based system (Du, et al., 2019).

The typical example of Layer-based modular system is shown in Figure 10, this module system is design by Project "4RinEU" (4RinEU, 2016). In this system, the supporting structure, insulation materials and renewable components are attached layer by layer, which can avoid thermal bridges, but the feature of heavy weight is not suitable for the renovation of high-rise buildings.

Plug-N-Harvest represents the idea of a Frame-based modular system (PLUG-N-HARVEST, 2017), shown in Figure 11. Insulation materials and renewable components are surrounded by a grid frame, which is directly fixed to the existing facade. This can potentially reduce the weight and thickness of the walls, but the metal frame can create thermal bridges.

For the Combination of Frame and Layer-based system, shown in Figure 12. In the project of MeeFS (MEEFS RETROFITTING, 2012), they designed the combination system that provides a continuous insulating layer between the load-bearing frame and the existing facade can significantly reduce the contact area between the existing facade and the metal frame. However, due to the fixed support, thermal Bridges still exist.

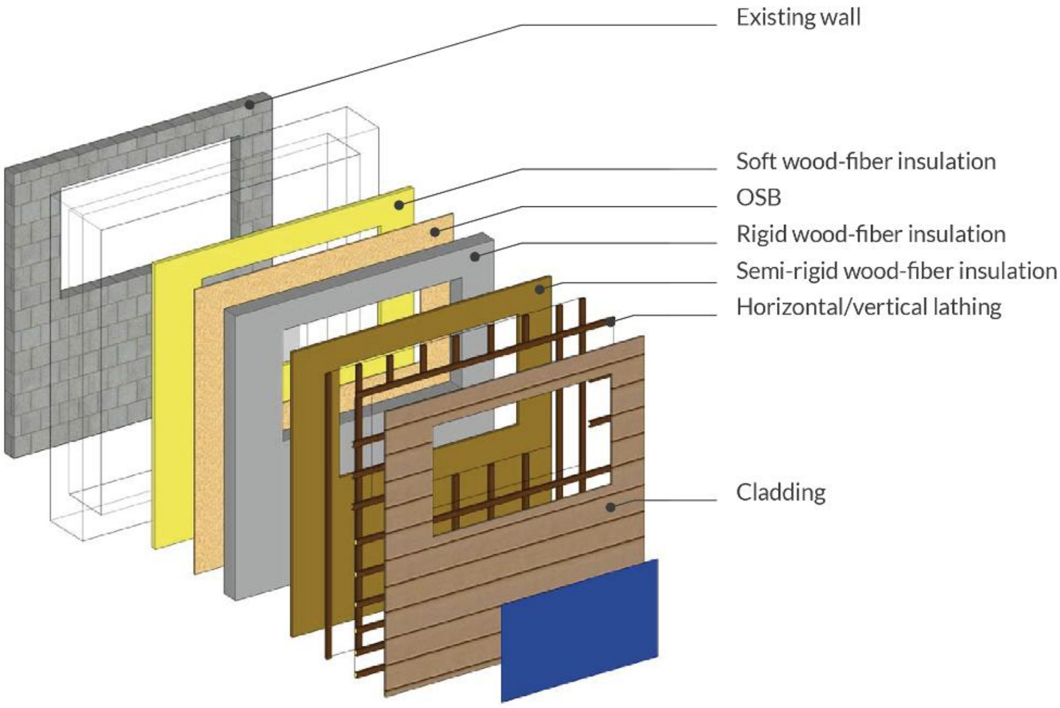


Figure 10 Layer-based Module System
[From: 4RinEU (4RinEU, 2016)]

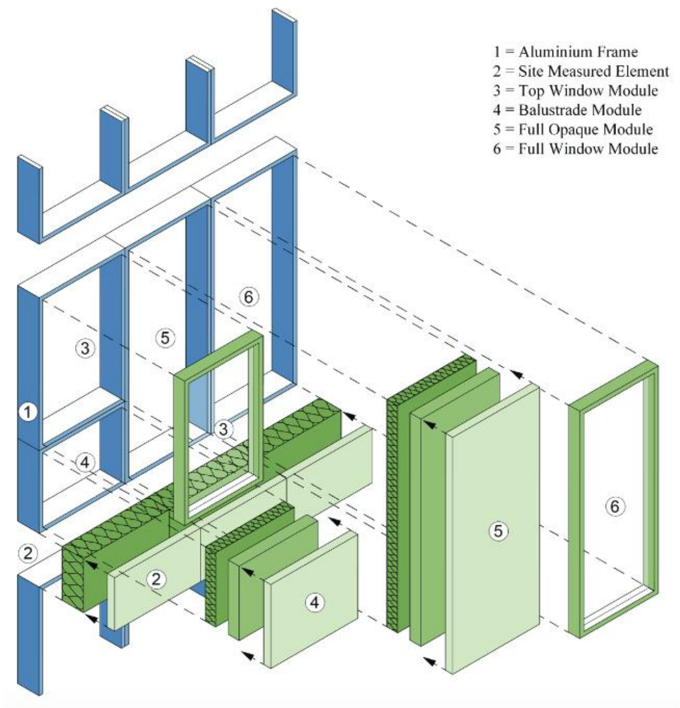


Figure 11 Frame-based Module System
[From: The PLUG-N-HARVEST Façade (PLUG-N-HARVEST, 2017)]

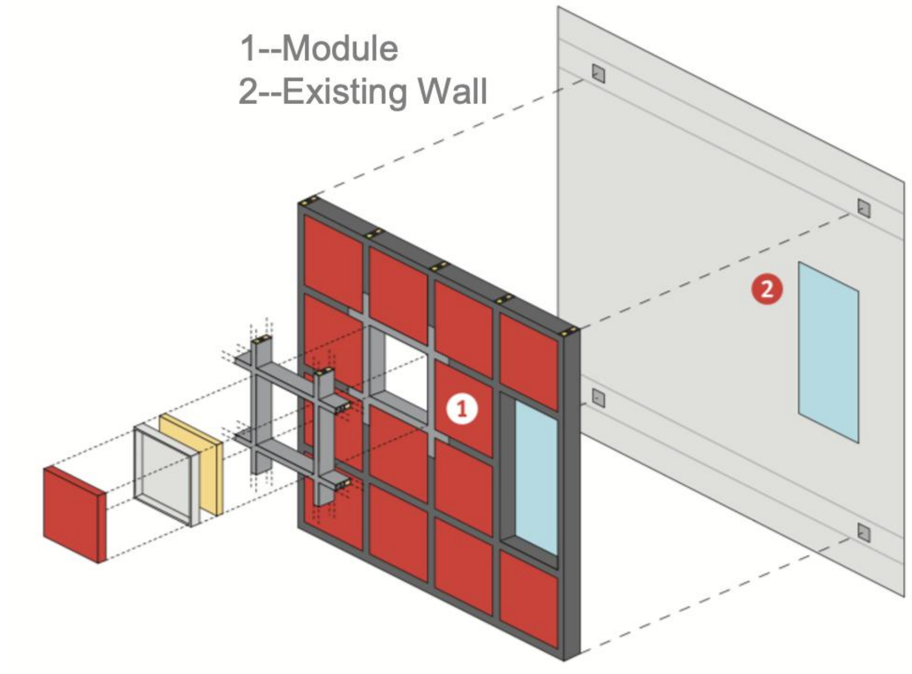


Figure 12 Combination of Frame and Layer-based system
[From: MeeFS (MEEFS RETROFITTING, 2012)]

3.6 Multi-criteria decision-making approaches for building retrofit

3.6.1 State-of-art of multi-criteria decision-making support

According to the reviewed literature, the commonly adopted methods of multi-criteria decision support for building retrofit are summarized into 3 categories: artificial intelligence (AI) models, simulation software and statistics hybrid algorithms. Thereinto, with the popularity and development of artificial intelligence (AI) in recent years, there is a new trend of combining artificial intelligence algorithms for the decision-making of building retrofit (Bocaneala, et al., 2025). AI models could be considered a more holistic approach. Statistical algorithms are the foundation of many artificial intelligence technologies, especially in machine learning, and simulation software can be used to test and validate AI systems, they are integrated into this larger multi-stage workflow. A complete artificial intelligence modelling process requires an overall approach to consider data, algorithms, evaluations, and deployments in a structured way (Datta, et al., 2024).

There is a challenge to develop the methods that can not only speed up the retrofit procedure, but also assist the decision-makers who are either professions or non-professions to understand the potential solutions rapidly at the early design stage (Ma, et al., 2023). Although simulation software and statistical hybrid algorithm have been developed and widely applicated for a long time, they are tending to be used for independent projects and requires certain professional skills (Olsson, et al., 2016; Boxer, et al., 2017; Ahmada, et al., 2017; Nik-Bakht, et al., 2020; Haruna, et al., 2021). AI models, in comparison, have the potential to provide the straight-forward and comprehensive schemes to whom does not have sufficient knowledge of building retrofit.

Differ from the liner processing of most statistical algorithms, AI models are considered as the comprehensive methods to comprise its own database. In recent years, there are few research projects have attempted to establish the databases of building retrofit approaches that can be further applied to data clustering and regression (Deb & Schlueter, 2021; Ma, et al., 2023). As this is an innovative direction, there are different attempts of AI models used for retrofitting or building manner. For instance, Cecconi et al. (Cecconi, et al., 2019) propose an AI model with ANN and GIS to predict the potential savings in energy efficiency retrofit, avoiding the expensive on-site condition assessment. The calculation for a single objective of "savings" is easy to obtain. However, for multi-objective projects, it is very cumbersome to distinguish or analyse construction methods based on various specific detail attributes. Amer et al. (Amer, et al., 2020) propose a computer-aided decision-making solution with the Non-dominate Sorting Differential Evolution (NSDE) and Adaptive Sparrow Search Optimization Algorithm (ASSOA), which are both integrated with the Genetic Algorithm (GA) to determine the possible retrofit solution under multi-objective. While Khansari and Hewitt (Khansari & Hewitt, 2020) utilise the concept of Agent-Based Model (ABM) to build a mathematic model in a traditional way to assist decision-making. Indeed, those AI model or integrated methods can be used to analyse building reconstruction cases and datasets with multiple indexes in a quantitative path. However, those attempts were considering objective problems to find the optimal solution, the process of reanalysing cases and datasets is necessary if encountering different demands. Furthermore, even though those different studies of AI models are designed for decision-making, some of them work for the detailed design stage and professional involvement is required.

Given this problem, the Case-Based Reasoning (CBR) enables decision-making fully to refer to other reference cases (Cheng & Ma, 2015), and provides suggestions or guidance for a broader range of users. In the past, due to the lack of similar reference cases for research projects, this approach has not received sufficient attention. As there are many records of building retrofit cases that have been done in the past two decades, especially for problems with many referenced cases, the CBR method has a broader application prospect (Wang, et al., 2019; Ahn, et al., 2020).

CBR approach can be an alternative method to reduce the duration of the research process in the early design stage, which is a promising solution for decision-making support in building retrofitting.

Due to this solution has not attracted enough attention from designers, there is not as much literature reviewed relevant building research on CBR currently. Some review descriptions can only be found in a few research papers (Ahn, et al., 2020). Ahn et al. (Ahn, et al., 2020) summarized 10 relevant investigations of the CBR system, in their research, they mainly discussed the information on various steps contained during CBR system itself. Such as the algorithms used for CBR, more detailly, the steps of distance calculation and weight determination for the algorithms. Chen et al. (Chen, et al., 2010) reviewed the application of some case-based studies in the field of building construction safety. Cheng and Ma (Cheng & Ma, 2015) concentrated on explaining the specific “4R” steps of the theory and workflow for CBR concept from Kolodner’s theory (Kolodner, 1992). Those research studies mainly focus on the general working steps or some specific principles of CBR.

Currently, the CBR research in architectural realm are more inclined to the use of multi-criteria decision tools to support the selection of optimal building strategies through mathematical models (Pohekar & Ramachandra, 2004; Asad, et al., 2012). The focus on retrofit construction is insufficient. An et al. (An, et al., 2007) pointed out the current application fields of CBR, mainly focusing on the construction period and/or cost estimation system, bidding decision system, method selection system and management system. For instance, Goodacre et al. (Goodacre, et al., 2002) analysed the heating and hot water energy renewal efficiency of English building stock through a cost-benefit analysis system. Their analysis includes fuel expenditure, CO2 emissions savings and potential health gains arising from the illness related to cold and damp. They set these conditions as attributes and review the expenditures in previous cases. And they set a time frame for their analyse, the results predict "an upgrading programme will exceed costs for discount rates up 14%."

Although these studies have analysed CBR from multiple perspectives, the internal indicators and comparison to other decision-making support approach have not been fully studied for building retrofit (Ma, et al., 2023). There is still a lack of systematic summaries of the internal details between the different methods used for decision-making, and the reason that CBR is more advantageous in early decision-making support for building retrofit compares to other approaches.

3.6.2 The Common Methods Used for Decision-making Support

In the field of artificial intelligent area, various algorithms and software are proposed to deal with the optimization of energy efficiency in buildings. It is worth emphasizing that the AI models, including CBR, are comprehensive decision-making models that normally contains the statistical algorithms and simulation software during the simulation or calculation process. According to the different development goals it can be composed of more than one algorithm or software during the modelling process. Statistical algorithms can be stand-alone, but AI models are hybrid.

In another word, there might not be a clear demarcation line between the AI models and the statistics hybrid algorithms in most cases. For instance, Delgarm et al. (Delgarm, et al., 2016) proposed a mono-objective and Multi-Objective Particle Swarm Optimization (MOPSO) algorithm coupled with Energy Plus to assess the energy consumption performance. The results show that the proposed optimization method can find the optimal solution in the form of an objective function in a short time. Figueiredo et al. (Figueiredo, et al., 2021) employed AHP to achieve the sustainable material choice integrating the BIM system. To extend the range of AHP algorithm employment, Haruna et al. (Haruna, et al., 2021) built a BIM model for developing sustainable building utilizing the enhanced AHP algorithm named ANP. Akaa et al. (Akaa, et al., 2020) developed a hybrid multi-criteria decision analysis tool based on the combination of Geometric Mean Method (GMM), AHP and TOPSIS to solve the optimisation between stakeholder's opinion and the design for fire-prove steel-frame building. To achieve different goals, AI models could adapt different algorithms in line with the specialises.

Similarly, combining with other algorithms is an essential procedure for CBR to realize the whole process. There are various of different approaches can be used for decision-making support, the characteristics they excel at are different.

From the reviewed research, some common methods are generated as follow:

Statistics hybrid algorithm/AI model:

- Case-Based Reasoning (CBR) is a "paradigm in artificial intelligence and cognitive science" (Leake, 2001). In areas where traditional rule-based or knowledge-based reasoning are relatively weak, CBR can provide solutions by analogy or referring to previous similar cases. (Perner, 1999; Fu & Shen, 2004; Hamza, et al., 2007; Bichindaritz, 2008; Chen, et al., 2010; Guo, et al., 2011; Cheng & Ma, 2015; Zhao, et al., 2019)
- The original Mixed-Integer Linear Programming (MILP) is an improvement of a row relaxation problem, and the simplex method is continuously used to solve it. Branch solving by adding constraints until the integer optimal solution appears at a vertex of the new improved relaxation problem. (Mejjaouli & Alzahrani, 2020)

- Agent-Based Model (ABM) simulates the action and interaction calculation model of autonomous agents, such as organizations/teams/etc. (Khansari & Hewitt, 2020) The MILP model and the ABM are two pure mathematical models with high precision and complexity.
- Sensitivity Analysis, which finds out sensitive factors that have a vital impact on the economic benefit indicators of the investment project from multiple uncertain factors and analyse and calculate the degree of influence and sensitivity on the economic benefit. (Gercek & Arsan, 2019; William, et al., 2021)
- Multiple Attribute Utility Technique (MAUT) and Sensitivity Analysis are theories in economics. Although the theory has a wide range of applications, its operation is complex with difficult that requires training in multi attribute utility functions. (Seyis & Ergen, 2017; Mosalama, et al., 2018)
- Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is an objective evaluation method by detecting the distance between the evaluation object and the optimal or the worst solution carries out the ranking. If the evaluation object is the closest to the optimal solution and the furthest away from the worst solution, the object can be determined as the optimal one. It can be used widely in general, but not in some special cases. (Seyis & Ergen, 2017; Akaa, et al., 2020; Ren, et al., 2021; Mukhamet, et al., 2021; Sánchez-Garrido, et al., 2022)

- Analytic Hierarchy Process (AHP) divides the various factors in complex issues into interconnected and orderly levels to make them organized. According to the subjective judgment structure of a certain objective reality (mainly a pairwise comparison), the expert opinions and the analyst's objective judgment results are directly combined to quantitatively describe the importance of elements at a level. (Gade, et al., 2018; Haroun, et al., 2019; Laguna Salvadó, et al., 2019; Zhao, et al., 2019; Akaa, et al., 2020; Moghtadernejad, et al., 2020; Ruggeri, et al., 2020; Mukhamet, et al., 2021; Sangiorgio, et al., 2022; Figueiredo, et al., 2021)
- ANP is a development method of AHP. To overcome the disadvantage of AHP, ANP can dispose the relationships among criteria and sub-criteria. It has a great performance in decision making when an extensive number of elements are involved. (Haruna, et al., 2021)
- Genetic Algorithm (GA) is an evolutionary algorithm that solves a population of individual solutions based on natural selection. (Mirjalili, 2019)
- Enhanced Archimedes Optimization Algorithm (EAOA) is an enhanced algorithm for Archimedes' optimization algorithm. It overcomes traditional shortcomings like local optimization and premature convergence. EAOA outputs the optimum values of minimum, mean value, and maximum value. In addition, it also has the minimum value of the standard deviation comparing with other algorithms. (She, et al., 2021)

- Decision-making Trial and Evaluation Laboratory (DEMATEL) and PROMETHEE II are variants of the AHP. But they significantly increase the difficulty and complexity. DEMATEL can calculate the degree of influence on other elements through the logical relationship between the elements in the system and the direct influence matrix. (Yadegaridehkordi, et al., 2019) The basic principle of PROMETHEE II is based on the pair-wise comparison of alternatives along each selected criterion. (Abedi, et al., 2012; Laguna Salvadó, et al., 2019)
- A Neural Network (ANN) is a new solution which can achieve many purposes. A neural network can be considered as either an AI model or an algorithm by itself, which can solve a series of problems by imitating the biological nervous system. The advantage of ANN lies in their powerful nonlinear fitting ability, which enables them to automatically learn patterns from complex data. However, the complex internal structure of ANN often leads them to be regarded as a "black box model", which is difficult to explain, and their training usually requires a large amount of data and computing resources. (Beccali, et al., 2017)
- Adaptive Sparrow Search Optimization Algorithm (ASSOA) is a new simulation-based optimization technique. It is a swarm intelligence optimization algorithm for sparrow foraging and evading predator behaviour proposed in 2020. Compared with the other optimization algorithms, ASSOA

achieves the lowest amount of the functions that have the most certainty. (Liu & Rodriguez, 2021)

- Non-dominated Sorting Genetic Algorithm II (NSGA-II) is a solid multi-objective algorithm by generating offspring using a specific type of crossover and mutation. While today it can be considered as an outdated approach. (He, et al., 2015; Lan, et al., 2019; Naderi, et al., 2020; Martínez, et al., 2020)
- K-Nearest Neighbour (KNN) is a non-parametric classifier. It is one of the first algorithms for data mining. It is commonly used for simple classification or regression problems as a "lazy learning approach". Yet, it also easily falls into the curse of dimensionality with the high-dimensional input of data. (Zhang & Zhou, 2007)

In terms of those analysed calculation approach, KNN is rarely used recently as it becomes increasingly inefficient due to its shortcomings in weight value. Besides of KNN, in fact, other solutions are all involves the weight calculation.

Simulation software:

- BECEREN is a tool developed by several companies focused on Life Circle Cost (LCC) only rather than being widely applicable. (Olsson, et al., 2016)
- BIM-based Design Iteration Tool (BIM-DIT) can support decision-making process by assisting the design team in the generation of design alternatives. It helps decision makers with precise knowledge of available options for

achieving truly sustainable building projects. Yet, it is not suitable for non-professionals (Ahmada, et al., 2017; Haruna, et al., 2021).

- Community VIZ GIS is a software focused on building intelligence, enabling a variety of functions. (Moghadam & Lombardi, 2019) The Construction Emission Evaluation tool is a tool used to evaluate the emissions level and impacts at different construction techniques and construction stages. (Sandanayake, et al., 2019) Both methods require experts to operate the software.

Besides those 3 simulation software, Open Studio, EnergyPlus, TRNSYS, DOE-2, ESP-R, eQuest, etc. are popular simulation packages that can be easily attached as well. These tools contain many features such as modelling and calculating energy consumption. However, the use of these tools requires professionals to limit their popularity. (Boxer, et al., 2017; Nik-Bakht, et al., 2020)

All these methods can be used to support the decision-making. But the operational difficulties vary. In addition, while a multi-criteria decision approach can be used to judge the performance of a retrofit strategy, users cannot maximize their selection of optimal cases that meet their specific needs. To this end, CBR mimics human reasoning that learn from the past experiences and adapt it to solve new problems (Cheng & Ma, 2015), which could provide decision makers with an intuitive solution. Thus, compared with the advantages and disadvantages of other AI models and algorithms, the characters of CBR are more suitable in early design stage.

Technically speaking, CBR can combine with most algorithms to fulfil the calculation and selection process, which completely depends on the purpose and ability of the designer. But in retrospect, one of the advantages of CBR is that it can provide an intuitive solution to people from different backgrounds, including non-professionals (Zhao, et al., 2019). Therefore, the concise algorithms or other simple data-processing methods would be much more preferred. The advantages and disadvantages of those reviewed decision-making approaches are listed in Table 2.

Table 2 Pros and Cons of various decision-making approaches

[Table by Author, (Li, et al., 2024)]

Function	Name	Pros	Cons
Statistics Hybrid Algorithm/ Artificial Intelligent Model	CBR	Provide similar solutions referring to previous cases even if in areas of weak knowledge	Easily affected by the quality of the database of cases
	MILP	Able to pick up the limitation of boundary for solutions	Only work for linear problems
	ABM	Suitable for complex system and target	Many parameters need to initialisation operations
	Sensitivity Analysis	Able to assess variables in precision	Require professional specialists to participate
	MAUT	Integrating multiple alternatives into a formula	Complex, too calculation steps
	TOPSIS	Coupled objective factor into decision process	Can't decide the optimal number of attributes
	AHP	Widely used, attributes defined by requirement	Subjective, can't generate new case
	ANP	Great performance when an extensive number of elements are involved	Must be technically considered from the decider's perspective
	GA	Obtaining/guiding the optimal search without explicit rules, reduces the difficulty of code implementation	Involves optimization, relatively complicated
	EAOA	Avoid the local optimization and premature convergence issue	Require operation in many times improving precision level
	DEMATEL	Fuzzy evaluation model	Evaluation can't be made in quantitative
	PROMETHEE II	Less step to calculate	Require additional information provided by deciders
	ANN	Eliminating the noise disturb	Require abundant training time and a large amount of basic data
	ASSOA	Achieves the lowest amount of the functions that have the most certainty	Limitations on data collection

	NSGA-II	Widely used in real-world applications	Need a solid benchmark to test against, considered out-of-date
	KNN	Simple and intuitive, easy to apply in data regression	No weight determination, crashes at high dimensions
Simulation software	BECEREN	The tool for calculating carbon emission for varies steps	Only focuses on LCC
	BIM-DIT	Provide knowledge of available options for achieving truly sustainable	Not suitable for non-professionals
	Community VIZ GIS	Realize multiple functions based on requirement	Require integrating in the software of GIS

Depending on the different building reference case datasets, some information hidden under statistics can be found. How to help users quickly select the most suitable case for their needs as a reference case is very worthy of attention. This goal requires the user to input corresponding demands, such as construction requirements, building information, etc.

Therefore, it is a necessary to develop a way to measure how similar a case is to decision maker's demands. The best cases for the customer can then be identified and matched. To this end, Case-based reasoning (CBR) could attain this goal (Kolodner, 1993). In this method, similar cases are searched from the corresponding database to match potential project solutions. There were a few research fully applied the principle of CBR approach to deal with the retrofit decision-making. For instance, in an Italian project "POI 2007-13" (Beccali, et al., 2017), the researchers built a database with 151 existing cases and used 2 ANN models to train the biological nervous system and compute the decision-making result. Zhao et al. (Zhao, et al., 2019) built a database of 71 retrofit cases in China to identify the attributes of the retrofitting buildings and implement the AHP algorithm for CBR approach in a real case in Shanghai to realize the retrofit procedure. Given that there is not much research in the current field where the CBR principle is applied to building retrofit specifically, Zhao, et al.'s research focused on systematically demonstrated the process of CBR. Thus, their outcome presented were merely a simple and broad guideline. For example, in the description of their outcome, case 23 represents "roof insulation", case 48 represents "window insulation film" (Zhao, et al., 2019). In the future research, presenting more information in the outcome can help decision-makers to have a better understanding.

Nevertheless, that research show that CBR is helpful in identify valuable information and extract potential solutions from similar previous solutions, which not only simplifies the preliminary research process in a large extent, but also guide the decision makers to make decisions more easily. The whole principle and workflow are worthy to be promoted and referred for retrofit in the early stage.

3.6.3 The Challenge of CBR for Decision-making Support in Retrofit

In the context of building retrofit, a field characterized by complexity and diverse requirements, CBR offers significant potential to enhance the quality and efficiency of decisions. However, applying CBR effectively in this domain involves considerable challenges.

There is clear claim (Perina, et al., 2017) pointed out that the completed sustainable retrofit projects have accumulated a great deal of reference experience. The foundational step in constructing a CBR system is defining a set of attributes that effectively capture the essential features of each case. In building retrofit, this proves exceptionally difficult. Existing retrofit projects are typically unique, self-contained cases. Documentation, such as project reports or publications, is often authored by different teams with varying objectives, leading to inconsistent emphasis, interpretation, and definition of key parameters. For instance, in Liu, et al.'s research, they emphasised the policies and barriers during building sustainable retrofit (they defined as "building green retrofit") (Liu, et al., 2020). In Ma et al.'s research, they proposed a multi-criteria decision support model for retrofit based on 152 cases, "the retrofit cost", "thermal insulation requirement", and "total retrofit area" were chosen as the attributes (Ma, et al., 2023). Park, et al. applied CBR to predicting the cost for construction for retrofit (Park, et al., 2025). Cost, as a relatively intuitive attribute, is easy to make horizontal comparisons.

However, according to different researchers' definition, some other attributes such as energy or component are subjective. In Zhao et al.'s research, they proposed AHP for CBR, so the model needs hierarchical calculation which requires hierarchical attributes. In the description of attribute Settings in Zhao et al. 's research, except for some direct general information, "component information" and "energy and cost information" were chosen for first-level attributes. They define these attributes as the user's choices. The second-level attributes for "Component" consists of 4 conditions (Zhao, et al., 2019. Page 5). However, in Liu, et al.'s research (Liu, et al., 2024), as they used different algorithm—random forest (RF), the way of setting attributes for calculation is different. Moreover, even in the similar classification of "System and component", they presented 6 conditions.

In addition, the challenge of extracting comparable attributes is intrinsically related to the scale of the case database. Although a small, homogeneous database is easier to build, it often lacks the diversity needed to draw reliable conclusions for a wide range of new problems or find truly similar cases. The accuracy and reliability of the CBR system are directly related to the breadth and depth of its underlying knowledge base.

The purpose of different research, the source of data acquisition, and different permissions, etc., all these factors bring difficulties to the establishment of the database. This consideration is also discussed in Liu, et al.'s research (Liu, et al., 2024, Page 2), they mentioned:

> *"Despite the fact that CBR provides an executable methodology frame, many challenges remain in multifarious sections, such as distance measurement, attributes selection, weights assignment and threshold of reuse cases. At present, rarely unified approaches have been found to collect and standardize the textual information of existing building green retrofit cases."*

Therefore, the current research team mainly determines the horizontal comparison attributes based on their own demands and existing data sources. For those professional research teams working on the similar topic, Zhao, et.al, researched 71 projects (Zhao, et al., 2019), Ma, et.al, reviewed 152 cases (Ma, et al., 2023) and Liu, et al,. analysed 109 cases (Liu, et al., 2024). In terms of quantity, when the attribute set is relatively small and the number of cases exceeds 100, the computational stability of the database can be relatively guaranteed. In Zhao, et.al's research, based on 71 projects, attributes within "component" such as "Insulation level of building envelope", "Energy-efficient level" and "Water-efficient" were all described as "Fuzzy terms" (Zhao, et al., 2019. Page 5).

Building a large and high-quality database is an important task that requires a significant investment of manpower and time in the initial stage. Each case must be carefully collected and analysed, decomposed into predefined attribute patterns, and then input into the system, this step requires the participation and judgment of experts. This process not only involves data input but also knowledge engineering - distilling tacit expertise and unstructured project reports into structured, machine-searchable data. However, this early-stage investment has created a powerful network effect. Once an abundant and extensive database is established, it will become a very valuable asset. For future users, the system offers abundant cross-references and instant access to the real retrofit case. The professional knowledge analysed by early experts can also be promptly retrieved to users directly, to improve efficiency of researching and decision-making.

3.7 Summary

Within the Design Research Methodology (DRM), CBR operates as a critical enabler for the decision-support phase, translating aggregated historical cases into actionable retrofit strategies. For example, during the pattern recognition stage of DRM, CBR retrieves and adapts prior successful modular solutions (e.g., prefabricated solar façades for 1960s concrete buildings) to new contexts (Juan, et al., 2010), while the DRM's iterative structure ensures these solutions are refined through stakeholder feedback and validated against multi-criteria benchmarks (e.g., energy savings, cost, heritage compliance). Thus, CBR is not a standalone tool, but a data-driven component embedded within the DRM's broader workflow, which also integrates predictive modelling, stakeholder co-design, and policy alignment (Asadi, et al., 2012).

By embedding CBR into the DRM, this research addresses a key limitation of conventional MCDM methods—their inability to adapt to the unique complexities of modular retrofits, such as balancing standardization with site-specific constraints. The DRM-CBR synergy ensures that decisions are both *evidence-based* (grounded in historical performance) and *future-proof* (adaptable to evolving technologies and regulations), positioning it as a scalable methodology for achieving systemic decarbonization.

Collectively, this review not only contextualizes the urgency and feasibility of retrofitting the UK's post-war housing but also identifies critical gaps in current research. While existing studies prioritise isolated retrofit measures or single-building case analyses, few systematize scalable methodologies that integrate modular design, renewable technologies, and stakeholder-centric decision-making.

This gap underscores the necessity of the Design Research Methodology (DRM) proposed in this thesis, which bridges modular retrofit theory with practical, replicable implementation. The following chapters provide a comprehensive scaffold to situate this research within the evolving discourse on modular retrofit.

4 Case-Based Reasoning Approach

4.1 Introduction

Building on the critical insights from the literature review—which established modular design, energy-efficient retrofits, and multi-criteria decision-making as foundational pillars for systemic building upgrades—this chapter introduces a **Case-Based Reasoning (CBR)** framework tailored to address the complexities of modular retrofitting. The literature underscores the potential of a design methodology for retrofits to streamline workflows, yet gaps persist in translating historical data into actionable, context-specific solutions. This chapter bridges that gap by interrogating three core challenges:

1. Accelerating Critical Workflow Phases

   Modular retrofits involve multi-layered decisions, from technology selection to stakeholder alignment. *Where in this workflow can CBR most effectively reduce delays?* Wang et al. also proposed a lesson mining system that uses CBR to help decision-makers avoiding possible accidents in their research. For instance, when making decisions on construction projects, they could present previous accidents of the explosives manufacturing plant to reduce the risk or other potential problems. This LMS is based on their own developed curriculum database, allows policy makers who may not fully trained in architecture to learn from existing experience effectively. By automating the retrieval and adaptation of proven solutions from historical cases, CBR slashes planning time by 30–50% (Wang, et al., 2019) while enabling stakeholders to bypass trial-and-error approaches. This strategy can be applied to modular retrofits as past cases can be displayed to reduce research time for the retrofit projects with similar conditions.

2. A Decision-Support Framework for Modular Retrofits

   Traditional retrofits rely on fragmented, linear processes ill-suited for modular scalability. In contrast, this chapter proposes a CBR-driven framework that redefines decision-making through three innovations:

   - Dynamic Knowledge Integration: Aggregating retrofit datasets (energy savings, costs, user feedback) into a searchable repository.
   - Context-Aware Recommendations: Matching building profiles (e.g., 1960s concrete frames) to modular solutions (e.g., prefabricated solar façades) using similarity metrics.
   - Stakeholder-Centric Weighting: Balancing competing priorities (e.g., cost vs. carbon reduction) via adjustable criteria rankings.

3. Balancing Multi-Dimensional Demands (Weights) in CBR Design

   To ensure reliability, the CBR framework is rigorously structured into three research phases:

- Phase 1: Case Clustering – Classifying buildings by retrofit potential (e.g., structural integrity, energy demand profiles).
- Phase 2: Case Retrieval – Deploying hybrid algorithms (e.g., KNN + fuzzy logic) to identify the top 5% most relevant historical cases.
- Phase 3: Solution Ranking – Applying Analytic Hierarchy Process (AHP) to prioritize retrofit options based on weighted indicators (e.g., 40% energy savings, 30% cost, 30% occupant comfort).

4.2 CBR Approach for Modular Building Retrofit

4.2.1 CBR Workflow

Case-Based Reasoning (CBR) differs from other AI approaches such as Knowledge-Based Systems (KBS) (Roth & Jacobstein, 1994) in several ways. Rather than relying solely on general knowledge of the problem domain or correlating along general relationships between problem descriptors and conclusions, CBR uses specific knowledge of prior experience and specific problem situations. CBR also provides incremental, continuous learning, because each time a problem is solved, a new experience is retained and can be applied to future problems. The common understanding of CBR concept is shown in Figure 13.

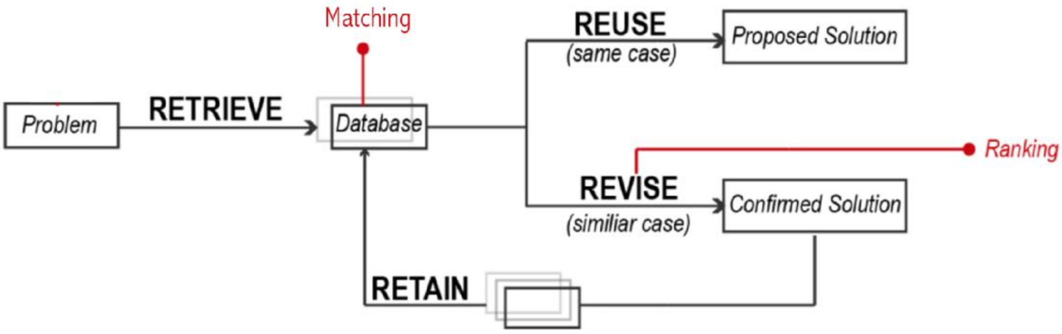


Figure 13. Concept of CBR
[Image by Author (Li, et al., 2024). Concept adapted from Kolodner (Kolodner, 1992)]

For the benefit of architects, after comprehensively evaluating the performance of various cases, it is crucial to help decision makers select the most suitable case for their needs in terms of candidate building information. The core of the CBR method is to extract successful previous cases or solutions from the datasets by measuring the similarity level. Therefore, to provide an adequate reference scheme, a summary database must be established. Valuable cases from the past are placed in this dataset, waiting to be selected for matching the target cases. Four sections constitute the entire CBR system, as shown in Table 3.

Table 3 Four sub-sections of CBR system
[Concept adapted from (Kolodner, 1992)]

Name	Purpose
Core Database	Store previous cases and solutions
Attributes database	Store case attributes
Measure method	Calculate similarity level
Modification method	Adjust the similarity computation method

However, in the practical perspective, how to determine the problem and input the demands into the CBR system might also be ignorant. According to this problem, Finnie and Sun (Finnie & Sun, 2003) raised an improved "R5" CBR model based on the original "4R", consisting of five steps: represent, retrieve, reuse, revise and retain.

This redeveloped theory is also gaining acceptance from many researchers, since "Represent" is also a crucial part in this learning cycle that determine the problems and structure the information at the first stage (Wang, et al., 2019).

Table 4 gives the names of individual steps and their corresponding effects. The most important stage among is the "Retrieve" stage, which is to match the case by evaluating similarity. The core is the attribute database that stores previous case information and the information for related retrofit buildings. In addition, the database retains case property information that is used to calculate similarity.

Therefore, considering that each attribute has different important characteristics, it is necessary to introduce weight coefficient to improve the accuracy of similarity measurement. The weight value is combined with the similarity calculation to generate the final project that best meets the decision maker's needs.

Table 4 Five significant steps constituting CBR system
[Concept adapted from (Wang, et al., 2019)]

Step	Function
Represent	Identify the problems and the demands for outputs
Retrieve	Pick out the similar case from database
Reuse	Use the chosen case as target reference
Revise	Adjust solution to adapt new condition
Retain	Store new solution and corresponding cases in database

4.2.2 A Decision-support Framework in CBR Cycle

The database in the CBR cycle contains attributes and related information for the projects that are worth learning from. In the following part of the weight grading scheme, according to the retrofit goals and demands, appropriate statistical methods are used to sort various situation. Therefore, to compensate for the shortcomings of the ranking method, the CBR system focuses on searching suitable cases based on the general information of the target building, such as year/type/size/climate/cost, etc (Zhao, et al., 2019). These attributes determine the result of similarity calculation. The characteristics of each step are summarized below:

1. Represents: The goal of CBR is to find cases matching the target cases at a high level. So, the first step is to set a clear goal. It's entirely up to the decision maker. It is important to note that the various attributes of the target must be the same as the case in the database, otherwise the attributes matching the target cannot be calculated.

2. Retrieval: The retrieve phase is the most important part of a CBR solution. Similarity measurements are needed to assess closeness. The concept of similarity includes three types: surface similarity, derivative similarity, and structural similarity (Mantaras, et al., 2005; Cheng & Ma, 2015). Those three types are all proposed from the perspective of attribute form, without considering measurement methods. Surface similarity refers to the basic information of the targets. For example, the features of cases such as size, application, location, etc., are the basic data for calculating surface

similarity. The derivative similarity is calculated between the deductive attribute value and the target. Deductive statistics are generated from basic information such as the area obtained by the product of side lengths. However, this kind of data is usually produced by simple manipulation of surface data and only changes in surface information. Conversely, another analogous concept called structural similarity derives from complex calculations, such as graph measures and first-order terms (Mantaras, et al., 2005). In this case, the structural properties of the case need to be determined first, and then the corresponding similarity level calculated. Other functions and algorithms such as neural networks are usually integrated into the process. Table 5 shows the comparison of the above three similarity qualities.

Table 5 Comparison of surface, derived and structural attributes
[Concept adapted from (Mantaras, et al., 2005) (Cheng & Ma, 2015)]

Name	Concept	Relative Parameters	Difficulty
Surface similarity	Surface information similarity	Case basic attribute	Low
Derivative similarity	Derived info generated from surface information similarity	Simple operation of case basic attributes	Low
Structural similarity	Internal case structural similarity	High order operation of case internal data	High

During this phase of CBR model, a corresponding database should be firstly established to support the similarity measurement. Then, depending on the implementing demands, appropriate algorithm will be combined to determine the weight precision for realizing the functionality needs. For instance, according to afore-mentioned algorithms in Section 3, Kim et al. (Kim & Kim, 2010) utilized a CBR structure with weight decision method of genetic algorithm (GA) to predict budget level under inputting some basic attributes of bridge such as width, location etc. It achieved the cost estimation of bridge construction based on previous data collection. Another example is a CBR solution proposed by Zhao et al. (Zhao, et al., 2019) in 2019 was regarded as the specific method used in future research. In this article, the authors adopted CBR method to extract the best matched building retrofit case from the collection database including previous sustainable building retrofit plan. In addition, the weight value was determined by AHP solution which could be validated via consistency checking process, in which the precision of weight calculation was guaranteed.

3. Reuse, Revise and Retain: The final part of CBR process can be understood as a combination if those three steps. Application of computed result by pre-similarity calculation is realized in this part. In reuses section, the selection case is chosen to solve issue, but in some cases, this stage could also go back to aid in enhancing model performance (Mantaras, et al., 2005). Revise section adapts the issue proposed process situation after reusing process which is commonly integrate into the reuse step. The last section of retain is to store the research outcome to database under special format. However, database establishment should consider its simplicity and efficiency feature ensuring the valuable of this dataset serving for decision makers. The space for storage also limits the dataset to some extent, simultaneously. Consequently, some solutions have been proposed to filter and remove useless cases from dataset (Ontañón & Plaza, 2003).

Following Table 6 presents relative major information of weight determination solutions used in CBR research related to building design in recent years.

4.2.3 Multi-dimensional Demands (Weights) in CBR Model

CBR cycle essentially is similarity calculation, which compute the weight coefficients for diverse cases to find the most similar case. Consequently, how to calculate this indispensable value of weight is the core of CBR studied solution.

Similarity calculation of CBR is generally classified into two types of weight factor and non-weight factor computation. In terms of non-weight factor computational approach, it is an original investigated manner that simply measures the mathematic distance number without any corrections, such as KNN (Zhang & Zhou, 2007). Although this is a simple solution to manipulate, the diverse features of the input attributes are neglected. Therefore, final precision would be impacted significantly (Ahn, et al., 2014).

Due to the characteristic of KNN is non-weight calculation that normally cannot be used independently in the cycle of CBR if the datasets are complex in dimensionality. The condition of using KNN for CBR is in combination with other algorithms and involves optimisation, could be considered as another direction for further work. In Cheng and Ma’s research (Cheng & Ma, 2015), the CBR cycle is built based on an ANN model, which completes the calculation process to filter the most similar cases. The KNN concept here was used for the “reuse” step based on a "trial-and-error" process, which needs certain work of repeat computing, to test out the optimal case. Faia et al.'s (Faia, et al., 2017) research follows a similar practice aiming in optimisation. The similar results were obtained by repeated calculations using KNN, and the Particle Swarm Optimization (PSO) were combined to optimise the selection of the variables. Therefore, once related to weight determination, KNN's weaknesses are obvious.

To cope with this issue, weight factors are integrated into system to improve the accuracy and calculation procedure. Table 6 analysed the weight determination solutions used for CBR model in architectural related research.

Abbreviations for Table 6

AER	Absolute Error Ratio
AHP	Analytic Hierarchy Process
ANN	Artificial Neural Network
GA	Genetic Algorithm
GDM	Gradient Descent Method
GMM	Geometric Mean Method
KNN	K-Nearest Neighbours
MAD	Mean Absolute Deviation
MAE	Mean Absolute Error
MAER	Mean Absolute Error Rate
MAPE	Mean Absolute Percentage Error
MER	Modulation Error Ratio
MRA	Multiple Regression Analysis
MSD	Mean Standard Deviation
PSO	Particle Swarm Optimization
RL	Reinforcement Learning
SER	Standard Error Rate
SHAP	SHapley Additive exPlanation

Table 6 Relative information about CBR investigations

[Table by Author, (Li, et al., 2024)]

Weight determination solution	Application	Integration with other methods	Validation	Tim e	Author
AHP	Method improvement	GDM	MAER	2007	(An, et al., 2007)

	Prediction	No	No	2008	(Wang, et al., 2008)
	Prediction	No	MAE	2009	(Chou, 2009)
	Prediction	No	No	2010	(Chen, et al., 2010)
	Method improvement	No	No	2014	(Ahn, et al., 2014)
	Prediction	No	No	2017	(Shen, et al., 2017)
	Selection	No	No	2017	(Xiao, et al., 2017)
	Prediction	No	MAPE	2017	(Ahn, et al., 2017)
	Selection	No	No	2019	(Wang, et al., 2019)
	Selection	No	Black-box/Experts	2019	(Zhao, et al., 2019)
	Prediction	No	MAPE/MSD/MAD	2020	(Ahn, et al., 2020)
	Selection	GMM	No	2020	(Akaa, et al., 2020)
	Selection	No	No	2021	(Okudan, et al., 2021)
GA	Prediction	ANN	SER	2010	(Koo , et al., 2010)
	Prediction	No	MAER	2010	(Kim & Kim, 2010)
	Prediction	MRA/ANN	SE	2011	(Koo, et al., 2011)
	Selection	No	No	2012	(Hong, et al., 2012)
	Selection	No	MAPE	2015	(Koo & Hong, 2015)
	Prediction	MRA/ANN	MAPE	2015	(Hong, et al., 2015)
	Selection	No	No	2017	(Jafari & Valentin, 2017)
	Prediction	No	MAPE	2020	(Kwon, et al., 2020)
	Prediction	No	MER	2020	(Jung, et al., 2020)
	Prediction	No	No	2020	(Chang, et al., 2020)
	Prediction	No	MAPE	2021	(Liang, et al., 2021)
MRA	Prediction	No	No	2012	(Jin, et al., 2012)
KNN	Prediction	PSO	No	2017	(Faia, et al., 2017)

RL	Selection	No	No	2022	(Guerrero, et al., 2022)
SHAP	Selection	4 Approaches in parallel	No	2023	(Ma, et al., 2023)
ANN	Prediction	No	AER	2011	(Ji, et al., 2011)
	Selection	KNN	Boolean	2015	(Cheng & Ma, 2015)
	Prediction	No	No	2017	(Beccali, et al., 2017)

As mentioned earlier, there are very few research implement CBR approach in architectural realm, specially building retrofit. It can be seen from the Table 6, around 2/3 research were done after 2015.

In the field of architectural research, the applications of CBR model mainly focus on prediction, and selection in the second place. Shown in Figure 14. Some CBR models may contain the combination of two or more algorithms would be defined by the primary algorithm shows in the first column in Table 6.

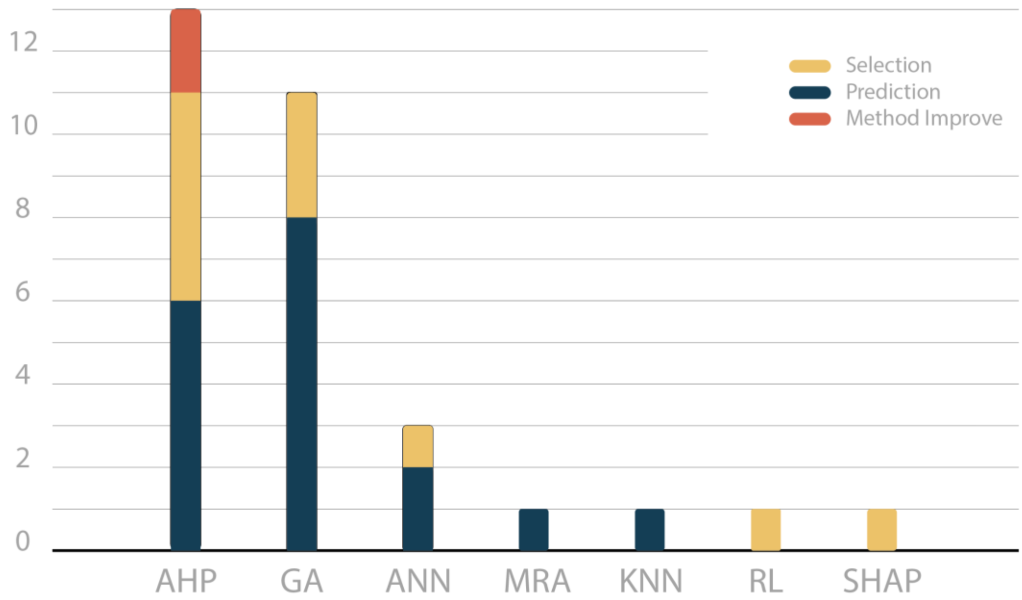


Figure 14 Percentage of Application in Algorithms

[Image by Author (Li, et al., 2024)]

The application of prediction pays attention to cost-estimation or risk evaluation rather than retrofit. It is important to emphasize that even though the contents of retrieval function among some studies may not as much as predictively research, each study includes the process of retrieving the matched cases from a database, which is the core part of CBR. For example, Ahn et al. (Ahn, et al., 2020) uses CBR to extract past empirical cases and improve the accuracy of construction budget estimation, the prediction was based on five normalized methods including interval, Gaussian distribution-based, Z-score, ratio, and logical function-based, which pre-process multiple attributes. Wang et al. (Wang, et al., 2008) utilised a CBR model to replace the traditionally intuitive estimation method, the result showed this new CBR solution could not only reduce the time for reviewing budget but also predict the cost effectively. Chen et al. (Chen, et al., 2010) collected 133 guilty verdicts from the court of architectural fatal construction occupational accidents (COA), which used AHP for classify and layer the problem and solution attributes, then weighted those attributes for determining responsibility and sentencing. This CBR model breaks the knowledge barrier for professionals by offering the judgement rules during construction, simultaneously, serves as a reference to the law attorneys for possible similar judgements in the future. Koo et al. (Koo , et al., 2010) regarded the sensitivity coefficients of ANN as the weight factors to compute mathematic distance and integrated with GA to predict the budget and construction duration of multi-family housing in line with specific features. Offering a clear indication while there still are limitations and uncertainties. Likewise, due to the uncertainty, Chang et al. (Chang, et al., 2020) built a multi-objective decision model, using GA, to evaluate the feasibility of the retrofit. This provides a guideline to the decision maker and benefits the framework for sustainable retrofit.

While in the view of selection, the purpose is mainly about building retrofit or knowledge learning. CBR has the great advantage in selecting the similar past cases to reduce the work of research. In the research of Okudan et al. (Okudan, et al., 2021), the Risk Management (RM) process usually integrated with multiple indicators, they developed a tool named CBRisk to support the RM processes as it is a knowledge-intensive process that requires effective related experience and knowledge, which bridged the gap between professional knowledge with the public. Another risk management research by Akaa et al. (Akaa, et al., 2020) combined GMM and AHP to study the portal-framed building cases, and support formulating the RM guideline based on AS/NZS ISO 31000:2009, to avoid the possible design of steel-framed buildings may expose to fires. Wang et al. (Wang, et al., 2019) also adopted this method in developing a Lessons Mining System (LMS) to search the most appropriate urban planning case for the decision maker as reference, which can help them to break the knowledge barrier, foresee and avoid the recurrence of potential problems. Xiao et al. (Xiao, et al., 2017) implemented CBR manner to build a model named Green Building Experience-Mining (GBEM), without weight factor correction, to perform green building retrofit design scheme based on the past renovation solutions. Jafari and Valentin (Jafari & Valentin, 2017) designed a decision-making framework by CBR, which learns the Life Cycle Cost (LCC) of past cases to consider a comprehensive economic goal for energy retrofits. Hong et al. (Hong, et al., 2012) investigated 362 cases in Seoul and used CBR to select the multi-family housing complex that has the effect energy saving potential.

In addition, the method improvement of how to assign values with high precision, is one of the research directions. In the principle initially proposed by Kolodner's (Kolodner, 1992), the weight values for CBR attributes should be determined by experts. However, due to the limitations of computer science at that time, calculating weights was a rather complex process. Nowadays, with the development of computer technology, the complex calculating processes of the 1990s can be replaced by computer algorithms. It is important to choose the appropriate algorithm according to different goals.

On this basis, considered the knowledge of experts were highly relied on personal experiences, some studies have also researched on how the computer science could better support the accuracy of determining weights by experts. For example, An et al. (An, et al., 2007) integrated AHP with Gradient Descent Method (GDM) for the CBR model to determine the specific weight in term of perfume cost estimation through computational process. With the same goal, Ahn et al. (Ahn, et al., 2014) developed an attribute weight-assessing method based on CBR model to critically measure the values, which improves the accuracy and efficiency of cost estimation in the computational procedure. These studies rely more on computer science, which is not a crucial consideration for building retrofit. It is worth to investigate for the researcher with professional computer backgrounds.

Among the research for those 3 applications of CBR, the algorithm is used independently in the majority situation as a straight-forward way to get. Thereinto, AHP and GA are the most widely used. As AHP has the advantage of layering attributes (Gade, et al., 2018; Laguna Salvadó, et al., 2019; Sangiorgio, et al., 2022), GA optimizes the ideal case considering multiple complex attributes based on similarity (Kim & Kim, 2010; Koo , et al., 2010).

Apart from AHP and GA, Jin et al. (Jin, et al., 2012) also introduced MRA into the CBR cycle to improve the accuracy of final cost prediction. However, due to the large number of independent variables, the calculation is rather troublesome, so statistical software is generally used in practice. Guerrero et al. (Guerrero, et al.,

2022) implied RL to train a “rial and error mechanism”. However, its shortcoming of requiring certain human engineering makes it hard to popularise. These two complex solutions are only suitable for multi-attribute determination problems. However, such a complex approach is costly and claims professionalism, which is not necessary for some simple building optimization projects.

Furthermore, to achieve multiple functions or goals, other algorithms can be combined within CBR cycle due to its simple internal logic and easy programming. ANN has its advantages to be integrated within CBR process. Based on the information of big dataset, ANN can predict the future results in a large range. Such as the afore-mentioned model of ANN and KNN combination by Cheng and MA (Cheng & Ma, 2015), they implemented the advanced non-linear solution instead of traditional linear solution to generate a new building LEED certification level based on previous LEED case database. Koo et al. (Koo, et al., 2011) integrates the prediction process with MRA and ANN, uses GA to optimize the optimization process of CBR model, realises the cost prediction function of early-stage construction projects based on 101 previous projects.

In terms of validation, most evaluation processes are combined with prediction as an indicator, to achieve cost estimation. Shown as Figure 15. Please note that this evaluation process is not mandatory for CBR model, in fact, most CBR models used for retrofitting design do not include this evaluation component.

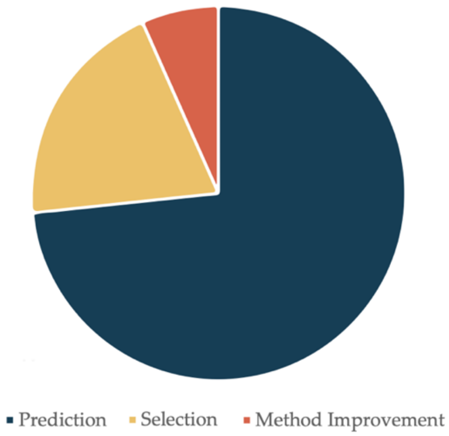


Figure 15 Purpose for Validation

[Image by Author (Li, et al., 2024)]

Several validation performance indicators are used to evaluate the errors during the procedure. Table5 shows that MAPE is a commonly used evaluation indicator, same with the MAER principle (Kim & Kim, 2010). Ahn et al. (Ahn, et al., 2017) disposed that the weighted Mahala Nobis distance solution is used to process the covariance effect of similarity measure into the engineering cost estimation based on the CBR-based MAER evaluation loss function. Hong et al. (Hong, et al., 2015) combined MAPE to evaluate the outcomes and compare the results with the basic CBR model, which shows the advanced CBR model has more accuracy. Other methods, such as MSD, MAD, etc., only target on some specific problems (Ahn, et al., 2020).

Thus, the key point, to develop a CBR model for selecting potential retrofit solution, is to determine the weighting factor. In the process of artificial algorithm development, a lot of research on solving weight factors has been carried out. In line with the results summarised above, the following section analyses and compares the primary algorithms used to determine weight factors for building retrofits.

(1) Analytic Hierarchy Process (AHP)

An American operational research scientist Thomas L. Saaty (Saaty, 1994) invented analytic Hierarchy process in 1970. The purpose of this method is to compare the significance degree for various cases based on multiple attributes. Contraposing to some qualitative standards, AHP could establish a hierarchy model to transfer the qualitative indicators into number pattern so that calculate weight for different properties. Pairwise comparison is the core solution for achieving the importance measurement. Through the method of pairwise comparison, the factors and properties of cases were compared to explore the relationship between them (Saaty, 1994).

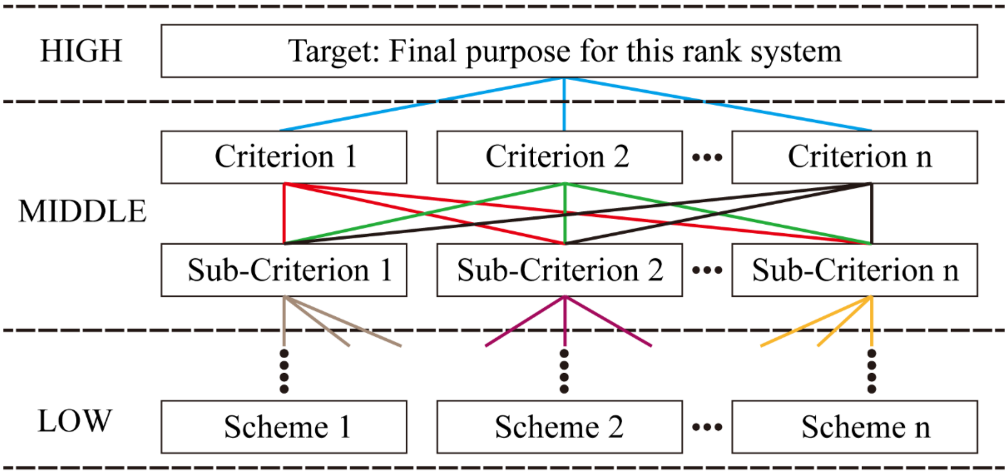


Figure 16 Construction of hierarchy for AHP
[Image by Author (Li, et al., 2024); Concept adapted from (Cui, et al., 2024)]

The first step of AHP is to establish a hierarchical model of the relationship between various factors. In general, this model consists of three layers: high, middle, and low. Show in Figure 16. Higher level determines the lower-level elements. That is, the result requires the product of the weights from each layer. After the model is established, the core step of weight calculation is to build the judgement matrix. Under this circumstance, all non-number elements can be converted into number pattern. This matrix means to perform pairwise comparisons of criterions. It should be noted that, the degree of relative importance for each element is assigned entirely according to human subjectivity. In addition, apart from the numerical transformation method, the level of the whole model is significance as well, because the weight of the computed results refers to the weight of the lower criterion against the upper one. In other words, the weight achieved each time is only the weight for this layer, and the result of the scheme is the product of the results for each layer. As mentioned, in Wang et al.'s research (Wang, et al., 2008), they adopted AHP method to generate the weight value of similarity calculation and estimate the retrofit budget of historical buildings. Chou et al. (Chou, 2009) proves that AHP has the best performance in the aspect of new construction cost estimation and achieves final architectural budget estimation. Zhao et al. (Zhao, et al., 2019) presents a comprehensive study of AHP with the interior model structure. They innovatively integrated AHP method with entropy solution to search appropriate green building retrofit case. Under this circumstance, the disadvantage issue of AHP in subjective could be revised via entropy manner.

At present, this algorithm has been frequently used among the reviewed studies. Its main advantages are as follows: first, the algorithm is intuitive, and the programming calculation is relatively simple. Second, users can assess or decide the weight order subjectively, which is in line with the differentiated hypothesis of user demands. Different from GA, which requires professional evaluation to eliminate impossible factors in advance to achieve the optimised solution. Although the result of AHP may not be the best option, it can ensure the results match the user demands.

Throughout the research process, it is important to provide users with an approximate result that meets their desired needs, even if the result is not optimal. In most cases, matching is not equal to optimisation. As mentioned earlier, the study of optimal solutions is an optimisation problem and can be regarded as another big theme.

(2) Genetic Algorithm (GA)

As the most used optimization algorithm in statistics, Genetic Algorithm (GA) is a computational model of biological evolution process that simulates natural selection and genetic mechanism of Darwin's biological evolution (Mirjalili, 2019). In essential, it is an approach searching for the optimal solution by simulating the natural evolution process. Comparing with other optimization manner, GA adopts the probabilistic optimization method, and the optimal search space can be obtained and guided automatically without definite rules, which decreases the code-achieved difficulty.

The significant point of GA is to determine the constraint rule firstly and then eliminate the weight factors not meeting the relative rules. That is to say, the best result of weight coefficient is generated after excluding other bad outcomes.

Afore-mentioned, Hong et al. integrated MAPE as a validation indicator during the calculation process (Hong, et al., 2012). GA is used as the basic algorithm for the CBR model, which obtains the weight factors of individual attributes and forecast the dynamic operational rating of residential buildings. The purpose of combining GA with MAPE is to enhance the optimisation and improve the accuracy. Koo et al. (Koo , et al., 2010) claimed that the implement of GA with CBR can improve the accuracy of optimal results and easy to manipulate for changing attributes during the process. In another research by Koo et al. (Koo & Hong, 2015), the CBR model was optimised by GA based on two criteria, RAW attribute weight range and MCAS, and the final prediction results were obtained.

In brief, the key point of GA is to determine constraint rules and exclude impossible weight factors in advance, which requires the participation of experts with professional background or rich experiences. As this algorithm is usually used to deal with optimization problem, which is relatively complicated.

(3) Artificial Neutral Network (ANN)

As the most widely used data-driven algorithm, ANN is, as Koo et al. declared, the “most superior among the methodologies for calculating the weight factors” (Koo , et al., 2010). ANN aims to seek the potential relationships between data hidden in database via imitating the structure of neurons in the human brains (Ji, et al., 2011). This kind of network depends on the complexity of the system and achieves the purpose of processing information by adjusting the inter-connection among many nodes (Beccali, et al., 2017).

In other words, ANN could adjust its own parameters to enable best results without re-constructing the entire model. According to the different logic framework of the model, neural network could be classified into multiple algorithms such as ANN, BPNN, CNN etc. (Ji, et al., 2011; Beccali, et al., 2017) ANN is a complex network structure formed by the interconnection of many processing units (neurons), which is an abstraction, simplification and simulation of the human brains' organizational structure and operating mechanism.

It is an information processing system based on the structure and function of brain neural network and simulates the activity of neurons through mathematical model. Shown in Figure 17.

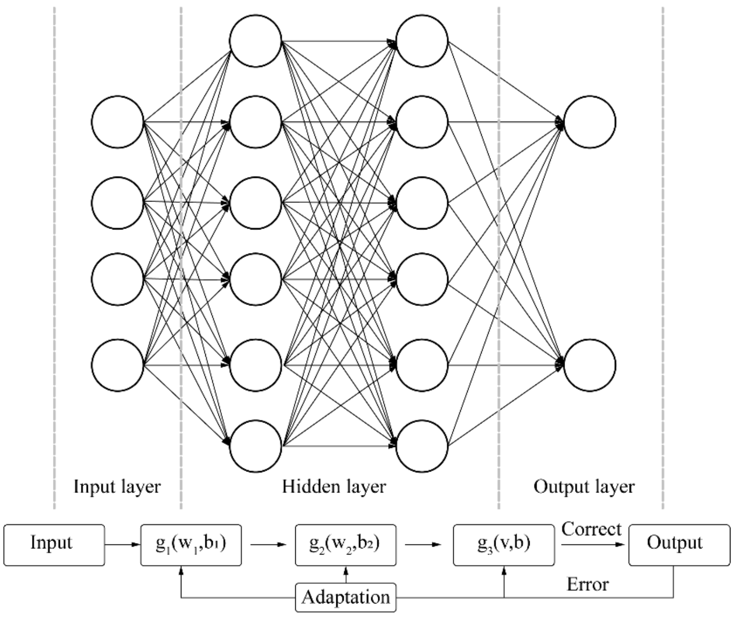


Figure 17 Typical structure of neural network and information transmission direction
[Image by Author (Chen & Li, 2021); Concept adapted from (Beccali, et al., 2017)]

In terms of determining the weight coefficients in CBR, ANN usually train the similarity distance immediately instead of searching for the optimal weight value, which is different from GA and AHP. However, among all weight factor determination methods, ANN is rarely used due to its complex internal structure, which is extremely unfriendly toward non-professionals.

4.2.4 Input and Output of CBR Model

The input is entirely depending on the demands from users. As summarised above, input mainly refers to surface similarity (Mantaras, et al., 2005; Cheng & Ma, 2015). For the CBR system, the surface similarity determines the characteristics of the building and represents the specific features of the reference building. In this case, the input data is the basis of code recognition. In general, the input data relates to the studied objectives and often expresses its multiple attributes. In line with the summarised results, two types of input information, basic construction data and objective data, cover the whole features needed for a building. Koo et al. (Koo, et al., 2011) implements this kind of data to perform cost estimation investigation in a CBR manner. Other objective data are more relevant to the ultimate purpose of the investigation. These objective data usually directly reflect the attributes related to research goals, such as building energy consumption, building retrofit costs, LEED evaluation, etc. Faia et al. (Faia, et al., 2017) applies the equipment parameters as the input data, to estimate the relative building energy consumption. The combination of these two types of data forms the input that is used to locate the similar reference case in the CBR system. Cheng and Ma (Cheng & Ma, 2015) proposed 6 types of basic building information that recognized by the U.S. Green Building Council (USGBC) as their input attributes for easier obtained values.

The output indicates the result of CBR utilisation. Through the review of the literature results, it can be concluded that the final output results include various forms, which include and not limited to specific case examples, cost, credits, criteria, laws, etc. All these patterns could be classified into one form of weight value. This is attributed that despite some research exporting target cases or other outcomes, all the results were constructed in line with the calculated scores under the CBR method. Consequently, the current output of CBR is essentially calculating the scores of different cases to pick out scenarios that meet the requirements.

4.2.5 Beneficiaries and Objectives

The beneficiaries of the CBR approach for architectural relevant issues mainly focus on two types of users: architects and stakeholders. For architects, the CBR method could assist them by providing multiple reasonable cases that reduce the efforts spend in researching. While for stakeholders, it could contribute to afford an intuitive understanding and foresee the possible building operational performance such as energy consumption, cost, façade exterior, etc.

In terms of objectives, cost estimation is the most significant target of relevant investigations at present (An, et al., 2007; Chou, 2009; Kim & Kim, 2010; Koo, et al., 2011; Ji, et al., 2011; Ahn, et al., 2014; Ahn, et al., 2017; Jung, et al., 2020; Ahn, et al., 2020). This is mainly because in general, the historical data related to the construction budget is sufficient to facilitate the establishment of the basic database.

Apart from this, sustainable building retrofit is another focus of attention. However, compared to cost prediction, the sustainable building retrofit investigation requires more details on buildings in line with disparate aspects to construct the reference datasets. Such complex information demands limit the development of CBR applications in building retrofit. Because of this, for other objectives, insufficient reliable reference data could lead to the impreciseness for CBR approach. Therefore, database-based performance determines how well a CBR solution runs.

4.2.6 Advantages and Disadvantages of CBR

The scientists acknowledged the advantages and disadvantages of CBR. On the positive side, remembering past experiences can help learners avoid repeating previous mistakes, and decision makers can identify which features of a problem are important to focus (Cheng & Ma, 2015). Another benefit is that the system learns by using fetch new cases, which makes maintenance easier (An, et al., 2007; Ahn, et al., 2014). CBR also enables the decision makers to quickly propose solutions to problems without fully trained with profession and explain open and ill-defined concepts (Cheng & Ma, 2015; Shen, et al., 2017).

On the negative side, some critics (Kolodner, 1992) claim that the main premise of CBR cycle is based on the anecdotal evidence, which adapting elements of one case to another. This process can be complex and lead to inaccuracies. However, recent work has enhanced CBR model with a statistical framework. This makes it possible for case-based predictions to have a higher degree of confidence and accuracy.

Besides that, the CBR input indicators reviewed for making retrofit are tending to choose the basic building information for surface similarity (Mantaras, et al., 2005; Cheng & Ma, 2015), which users can easily provide. However, the inputs that involve performance indicators such as energy consumption, carbon emission or equipment performance, etc., would be unfriendly to the unprofessional users. Therefore, it is necessary to further study how to realise a system that can dynamically express the energy status of buildings with the change of input parameters. This could translate the professional understanding of performance indicators along with the input of basic surface similarity.

4.3 Summary

This chapter establishes the theoretical and methodological foundations of the Case-Based Reasoning (CBR) framework for modular building retrofits, addressing the complexities of balancing technical, economic, and social demands in energy-efficient renovations. The CBR workflow—structured around a cyclical process of retrieve, reuse, revise, and retain—leverages historical retrofit data to generate context-aware solutions, bridging the gap between fragmented case studies and scalable, replicable strategies. Mainly include the understanding of:

1. CBR Framework Design: A systematic workflow integrating modular retrofit knowledge into a dynamic decision-support system, enabling rapid matching of building profiles to optimal retrofit strategies.
2. Multi-Dimensional Weighting: A hybrid Analytic Hierarchy Process (AHP) method to prioritize attributes based on stakeholder priorities and regional constraints, ensuring adaptable decision-making.

3. Input-Output Architecture: User-friendly inputs needed to be translated into technical queries, with outputs presenting ranked retrofit options, visual construction diagrams, and quantified performance benchmarks.
4. Beneficiaries and Objectives: Mainly for architects and stakeholders. Yet, the performance based on the database determines the operation of the CBR solution. Establishing a sufficiently complete database is a challenge, which will require a sufficient number of cases and analyses.
5. Advantages and Disadvantages: The positive side is obvious as CBR can translating the knowledge to the potential solutions quickly. The negative side is the setting of attributes might be complex and difficult, which requires the cooperation of experts and professionals.

This research is developing a prototype of CBR for modular retrofit, and the above conditions will have a certain impact on the prototype, this will be further discussed in the Scope of the next Chapter.

5 CBR Decision-making Support

5.1 Introduction

Building on the theoretical foundations of the Case-Based Reasoning (CBR) framework established in Chapter 4, this chapter transitions from conceptual design to practical implementation by developing a prototype CBR decision-support tool tailored for modular building retrofits. While the CBR model's robustness is theoretically validated, this prototype acknowledges inherent limitations—primarily constrained by the scope of available case data (e.g., Horizon 2020 projects) and regional specificity of retrofit practices. Nevertheless, the prototype serves as a critical proof-of-concept, demonstrating how CBR principles can translate into actionable insights for stakeholders, particularly for homeowners and small-scale contractors with limited technical expertise.

The chapter focuses on three core objectives:

- Case Study-Driven Technology Identification: Leveraging the retrofit cases from Horizon 2020， funded by EU (European Commission, 2014-2020). This phase identifies and categorizes key modular technologies (e.g., PVT systems, dynamic shading, prefabricated insulation) that have demonstrated scalability and efficacy in diverse contexts. By analysing project-specific outcomes, the prototype prioritises technologies with proven adaptability, such as solar-integrated façades from the PLUG-N-HARVEST initiative or geothermal retrofits from RenoZEB.

- Case Attribute Determination: This phase focuses on extracting and standardizing critical retrofit attributes from the limited yet diverse case study data, establishing a foundational schema for the CBR interface. The goal is to identify universally applicable metrics across heterogeneous projects (e.g., Horizon 2020 retrofits) while addressing gaps in data granularity and consistency. Key strategy is attribute extraction: Isolate recurring, decision-relevant parameters from case reports, such as *U-value improvements*, *energy savings (%)*, *installation time reduction*, and *cost per m²*, while filtering out niche or context-specific details (e.g., bespoke regulatory constraints).

- Interface Design: Developing an intuitive, user-centred interface that simplifies complex retrofit attributes (e.g., Energy Saving, Payback Time) into fuzzy, accessible inputs (e.g., "Energy Performance"). This bridges the gap between granular technical data and non-expert user needs.

5.1.1 Scope

5.1.1.1 Case Study: Horizon 2020 Projects in Envelope Retrofits

This research focuses on some selected Horizon 2020 projects targeting building envelope retrofits (e.g., façades, roofs) to establish a robust foundation for prototyping a Case-Based Reasoning (CBR) system tailored to modular retrofits.

- Why Horizon 2020 (H2020)? It is essential to obtain reliable sources, from official institutions or governments, with publicly available information for research. On the contrary, as enterprises need to consider operating profits or patent profits, the information available for disclosure is limited. Such as Liu et al. selected the retrofit case from the academic website of China National Knowledge Infrastructure (CNKI) for their research (Liu, et al., 2024). For this study, these retrofit projects from H2020 are rigorously monitored, peer-reviewed, and designed for scalability—critical traits for CBR training data.
- Why Envelope Retrofits? Façades and roofs account for 60–70% of building energy loss, making them high-leverage targets for modular solutions.
- Why These Selected Projects? These projects were selected for their alignment with the following criteria:

1. Modular Innovation: Each project emphasizes prefabricated, component-based solutions (e.g., plug-and-play solar façades in PLUG-N-HARVEST, timber-based modular panels in BERTIM), directly supporting the CBR model's requirement for standardized, replicable strategies.
2. Data Completeness: Publicly accessible datasets—spanning design specifications, energy performance metrics, cost breakdowns, and post-retrofit evaluations—enable granular analysis of *what worked*, *why*, and *under what conditions*. For instance, BRESAER provides quantified U-value improvements (0.8 → 0.3 W/m²K) and installation time reductions (40%).
3. Geographical and Technical Diversity: Projects span 15 EU countries and address varied climates (e.g., Mediterranean heat resilience in ADAPTIWALL, Nordic insulation in 4RinEU), ensuring the CBR prototype adapts to regional constraints.
4. Policy Relevance: All projects align with EU 2030 decarbonization targets, offering insights into regulatory compliance (e.g., NZEB standards in RenoZEB) and subsidy frameworks critical for real-world adoption.
5. Stakeholder Engagement: Detailed records of co-design processes (e.g., occupant feedback in HERB, contractor workflows in MORE-CONNECT) inform the CBR's ability to balance technical and social priorities.

By centring on Horizon 2020 initiatives, this case study ensures the CBR prototype is grounded in EU-funded best practices, validated against high-impact retrofit typologies, and scalable across the bloc's heterogeneous housing stock. The selected projects collectively represent over €180 million in R&D investment, embodying the technical rigor and innovation necessary to train a reliable, policy-compliant decision-support tool.

This scope ensures the CBR model learns from successes and lessons learned in Europe's most ambitious retrofit initiatives, positioning it as a transferable tool for accelerating the Renovation Wave.

5.1.1.2 Developing a Prototype & Setting Attributes

Many Horizon 2020 cases, while pioneering, lack comprehensive reports—critical attributes like cost or construction time are inconsistently documented, introducing training biases. For example, only part of those projects detail lifecycle costs, and emerging technologies remain underrepresented.

This chapter prioritizes establishing the CBR framework's architecture—defining retrieval algorithms, adaptation rules, and interface logic—rather than exhaustive data refinement. Dataset enhancement (e.g., filling attribute gaps, integrating global cases) requires future collaboration with industry partners, expert validation, and access to restricted repositories. By focusing on structural robustness, the prototype lays a scalable foundation for incremental improvement as richer data becomes available.

5.2 Case Study of Modular Retrofit with Renewable Energy Techniques

These projects named as Table 7:

Table 7 Nomenclature

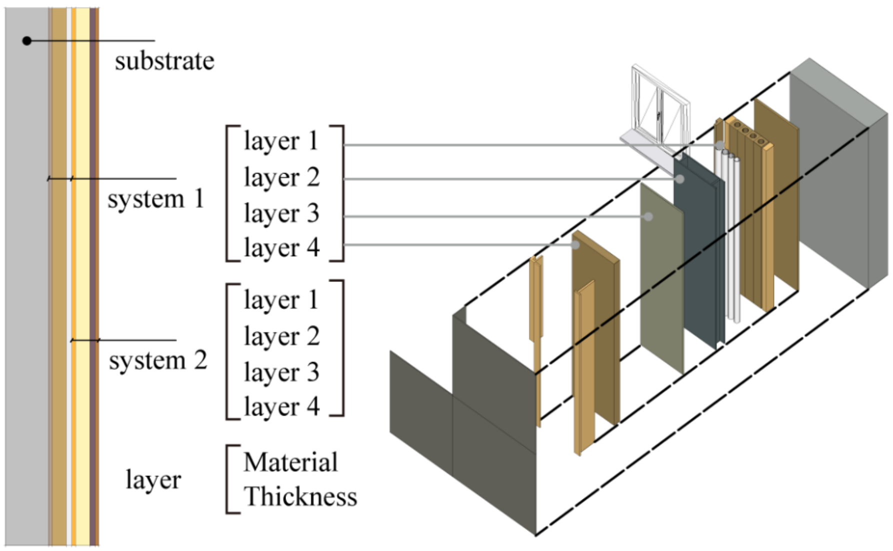
Abbreviation	Full name
4RinEU (4RinEU, 2016)	Robust and Reliable technology concepts and business models for triggering deep Renovation of Residential buildings in EU
A2PBEER (A2pbeer, 2013)	Affordable and Adaptable Public Buildings through Energy Efficient Retrofitting
ADAPTIWALL (ADAPTIWALL, 2013)	Multi-functional light-weight WALL panel based on adaptive Insulation and nanomaterials for energy efficient building
BERTIM (BERTIM, 2015)	Building energy renovation through timber prefabricated modules
BRESAER (BRESEAR, 2015)	Breakthrough solutions for adaptable envelopes for building refurbishment
BuildHEAT (BuildHEART, 2015)	Standardised approaches and products for the systemic retrofit of residential Buildings, focusing on heating and cooling consumptions attenuation
E2VENT (E2VENT, 2015)	Energy Efficient Ventilated Façades for Optimal Adaptability and Heat Exchange enabling low energy architectural concepts for the refurbishment of existing buildings
EnergyMatching (EnergyMatching, 2017)	Adaptable and adaptive RES envelope solutions to maximise energy harvesting and optimize EU building and district load matching
Envision (Envision, 2017)	Energy harvesting by Invisible Solar Integration in building skins
HEART (HEART, 2017)	Holistic Energy and Architectural Retrofit Toolkit
Heat4Cool (Heat4cool, 2016)	Smart building retrofitting complemented by solar assisted heat pumps integrated within a self-correcting intelligent building energy management system.
HERB (HERB, 2012)	Holistic energy-efficient retrofitting of residential buildings
ImPRESS (ImPRESS, 2015)	New Easy to Install and Manufacture Prefabricated Modules Supported by a BIM based Integrated Design ProceSS

INSPIRE (INSPIRE, 2012)	Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems
MEEFS RETROFITTING (MEEFS RETROFITTING, 2012)	Multifunctional Energy Efficient Façade System for Building Retrofitting
MF-RETROFIT (MF-Retrofit, 2013)	Multifunctional facades of reduced thickness for fast and cost-effective retrofitting
MORE-CONNECT (MORE-CONNECT, 2014)	Development and advanced prefabrication of innovative, multifunctional building envelope elements for Modular retrofitting and connections
PLUG-N-HARVEST (PLUG-N-HARVEST, 2017)	PLUG-N-play passive and active multimodal energy harvesting systems, circular economy by design, with high replicability for self-sufficient districts near-zero buildings
Pro-GET-OnE (Pro-Get-One, 2017)	Proactive synergy of integrated Efficient Technologies on buildings' Envelopes
ReCO2ST (ReCOST2T, 2018)	Residential Retrofit assessment platform and demonstrations for near zero energy and CO2 emissions with optimum cost, health, comfort, and environmental quality
REnnovates (REnnovates, 2015)	Flexibility Activated Zero Energy Districts
RenoZEB (RenoZEB, 2017)	Accelerating Energy renovation solution for Zero Energy buildings and neighborhoods
RETROKIT (RETROKIT, 2012)	RetroKit - Toolboxes for systemic retrofitting

5.2.1 H2020 Projects

This research aims to study the conditions of renewable energy utilization in the innovative retrofitting of modular systems. The renewable energy techniques used in modular retrofits are the core focus of this research. The following sections explore the project workflows, renewable energy technologies, and various details of the projects, such as installation methods, management systems, etc.

Figure 18 illustrates the ideal paradigm for building envelope structures, where each layer can be replaced with different materials and thicknesses. In this case, the paradigm can encompass all modularization solutions for building renovation, offering valuable insights for architects in the future.



Several layers constitute the entire wall construction. Furthermore, the layer can be comprised into two variants of material and thickness.

Figure 18 Ideal paradigm building envelope structure

[Image by Author (Li & Chen, 2020)]

In order to establish the CBR model, the first step is to conduct a database, which could be divided into 4 steps, as shown in Figure 19:

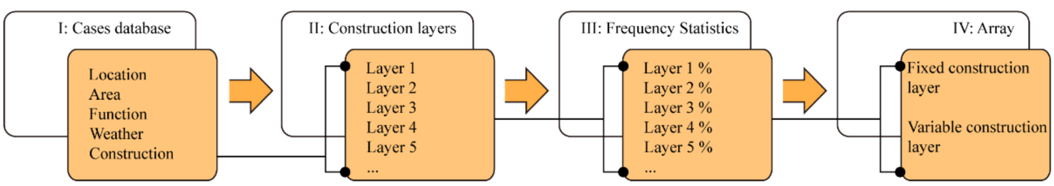


Figure 19 Workflow of CBR Database

[Image by Author (Li & Chen, 2020)]

a. Cases database:

The construction database needs to be shaped to fully account for all structures, enabling the exploration of common internal characteristics across all investigated cases. Based on the database created, relevant construction terms are selected to form the construction database, allowing for the investigation of the commonalities among these structures.

b. Construction layers:

   Each construction can be classified into various layers based on its function. In the following section, these functional tiers will form the common model for the structure of the building envelope.

c. Frequency statistics:

   Based on the dataset described above, which includes various aspects of the projects such as location, function, etc., it is essential to calculate the frequency of different types of layers in the construction of the envelope structure. The frequency of these layers indicates which layers are essential. Using the frequency statistics for different layers and the original construction described in the retrofit module design guide, a model is constructed according to the various functions of the layers. Note that this model is focused only on the functions of the layers, without considering attributes like size, thickness, or material type. Since the material and thickness of several layers affect the thermal conductivity of the envelope, the next section will introduce the relevant computational equations to calculate the thermal coefficients for the entire construction, influenced by material and thickness. Additionally, machine learning could automate this process via programming.

d. Array:

After completing the above steps, it is obvious that all constructions consist of two types of layers: fixed and variable. To finalize the structure database, it is essential to combine these two constructed patterns using a matrix method. Ultimately, all layers will form the paradigm for architectural external structures.

5.2.1.1 Technologies used in Case Studies

Based on the above, the selected projects have been reviewed, and the technologies used in these modular approaches can be summarized, shown in Table 8.

Table 8 Summary of Used Technologies in Case Studies

Abbreviation	Technologies	Module
4RinEU (4RinEU, 2016)	Solar collector; Photovoltaic	Layer-Based
A2PBEER (A2pbeer, 2013)	Lighting, Solar shading, Ventilation, Solar collector	Layer-Based
ADAPTIWALL (ADAPTIWALL, 2013)	Lighting, Solar shading, Ventilation, Solar collector	Layer-Based
BERTIM (BERTIM, 2015)	Facade materials	Layer-Based
BRESAER (BRESEAR, 2015)	Ventilation, Solar shading, Solar collector, Photovoltaic	Combined
BuildHEAT (BuildHEART, 2015)	Photovoltaic， Geothermal energy	Combined

E2VENT (E2VENT, 2015)	Ventilation, Solar collector	Layer-Based
EnergyMatching (EnergyMatching, 2017)	Photovoltaic	Combined
Envision (Envision, 2017)	Solar collector; Photovoltaic	Layer-Based
HEART (HEART, 2017)	Ventilation; Solar shading; Solar collector, Photovoltaic	Combined
Heat4Cool (Heat4cool, 2016)	Photovoltaic; Solar collector	Combined
HERB (HERB, 2012)	Lighting, Solar shading, Ventilation, Solar collector, Photovoltaic, Geothermal energy, Computer models	Combined
ImPRESS (ImPRESS, 2015)	3D Printed Facade materials for Insulation	Frame-Based
INSPIRE (INSPIRE, 2012)	HVAC, lighting and shading systems, Solar collector	Frame-Based
MEEFS RETROFITTING (MEEFS RETROFITTING, 2012)	Ventilation, Solar shading, PVT (Solar collector, Photovoltaic)	Combined
MF-RETROFIT (MF-Retrofit, 2013)	Solar shading	Layer-Based
MORE-CONNECT (MORE-CONNECT, 2014)	Solar collector; Photovoltaic	Frame-Based
PLUG-N-HARVEST (PLUG-N-HARVEST, 2017)	Solar collector, Photovoltaic (renewable energy generation and storage)	Combined
Pro-GET-OnE (Pro-Get-One, 2017)	Photovoltaic	Frame-Based
ReCO2ST (ReCOST2T, 2018)	Ventilation, Photovoltaic, Solar shading (smart windows)	Combined
REnnovates (REnnovates, 2015)	A standardised prefabricated energy module equipped with communication technology	Frame-Based
RenoZEB (RenoZEB, 2017)	Solar collector, Photovoltaic; Geothermal heat	Combined
RETROKIT (RETROKIT, 2012)	Solar collector, Photovoltaic	Frame-Based

5.2.1.1.1 Ventilation

The façade skin ventilation system primarily regulates interior temperature and facilitates the exchange of fresh air, improving the annual energy performance of retrofitted buildings by balancing heating and cooling requirements.

Construction: Common Features in Ventilation Module Façades

• The air cavity is an essential component in ventilation façades, providing the necessary space for airflow. This system utilizes the air cavity behind the skin panels to promote air circulation, helping to reduce humidity levels.

• The air cavity is positioned directly behind the finishing panels and in front of the insulation layer, which serves as the core layer. In this arrangement, the air layer helps prevent the formation of vapor in the insulation material.

• The skin panels can serve multiple functions, such as acting as a coating or providing fire resistance. The material used for these panels is not limited to any specific type; rather, any durable, multi-functional veneer can be employed as the finishing skin. This can also integrate other renewable energy technologies, such as BIPV (Building-Integrated Photovoltaics).

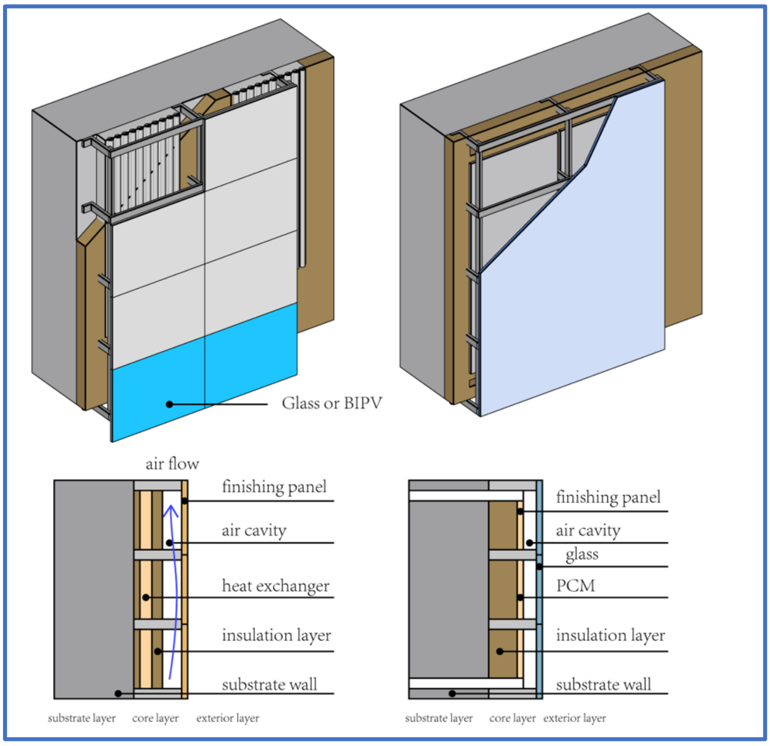


Figure 20 Ventilation facade system typical construction which may integrate other resource.

[Image by Author]

5.2.1.1.2 Solar Shading

Solar shading construction is typically used to block direct sunlight, with the goal of improving the annual energy performance of retrofitted buildings by balancing heating and cooling requirements. Some retrofit projects integrate this function into the external skin layer of the façade to provide shade from the sun. Solar shading is designed not only to block sunlight but also to prevent glare and mitigate the impact of direct sunlight. The solar panels can be adjusted according to the intensity of sunlight to enhance the cooling effect.

Construction: Common Features in Solar Shading and Ventilation Modules

• Solar shading construction consists of the basic component of solar shading panels. These elements can be made from various materials for different purposes, such as insulation and thermal storage. Additionally, applying the correct colour coatings on the surface of these materials can enhance their solar shading function.

• Solar shading constructions are typically modular, as they are often added to the façade or windows. Therefore, it is recommended to integrate them into the façade modules.

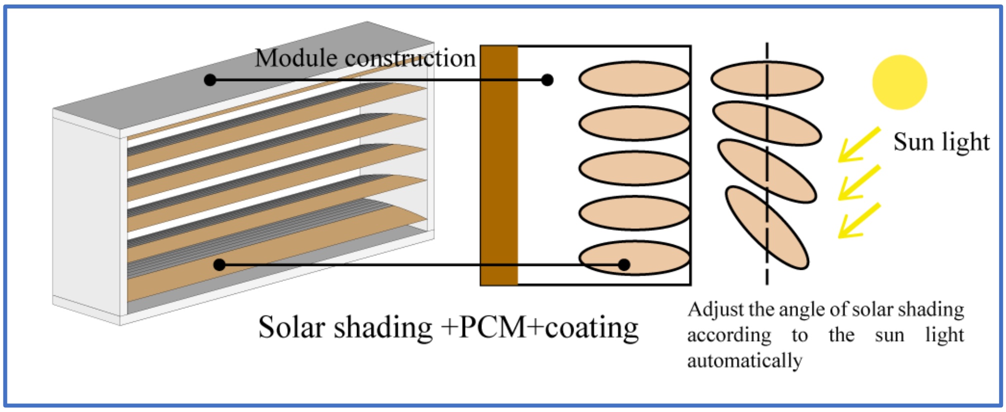


Figure 21 Multi-function solar shading modules
[Image by Author]

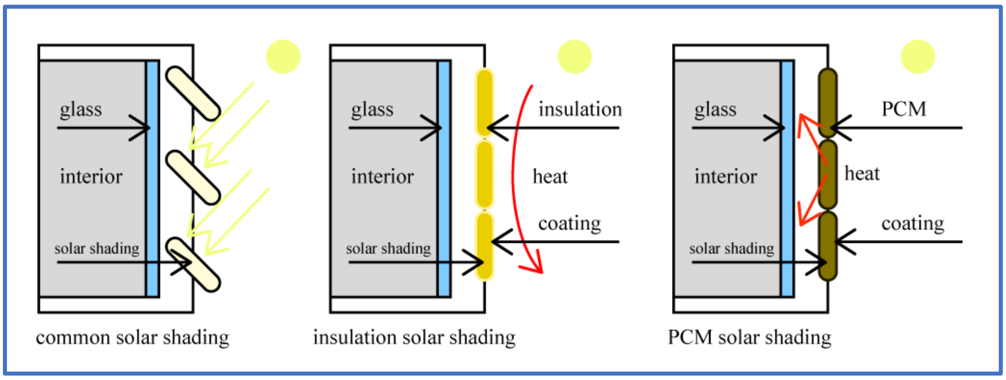


Figure 22 Multi-purposes of the solar shading construction
[Image by Author]

5.2.1.1.3 Solar Collector

Solar collectors refer to equipment that absorbs and releases solar energy, such as PCM (Phase Change Material). These systems are used to adjust indoor environments or heat water. Depending on requirements and modular construction, solar collector configurations can be summarized as follows:

Construction: Common Features in Solar Collector and Ventilation Modules

• Solar collectors require direct exposure to sunlight, so the skin material is typically transparent, like glass.

• Energy storage equipment, such as PCM, can be placed independently, without integration into the façade or system.

• PCM materials, which store energy, can be combined with insulation layers to form the supporting structure for the modular façade.

• No skin material is needed to cover solar collectors on the roof, as they don't require decoration.

• Combining PCM or solar tube collectors with small turbines can efficiently heat fresh air, improving indoor environments.

• Solar collectors generally come in three forms: tubes, folded plates, and energy storage. Tubes transfer heat via liquid in pipes, folded plates heat the air behind the finishing material, and energy storage collects and stores heat for later use.

• The positioning of solar collectors depends on the energy utilization pattern. For direct sunlight absorption, they are placed in front of the insulation layer, while for heat exchange with PCM, they are positioned between the insulation and substrate to improve efficiency.

• Solar collectors can be installed on any roof, but only equipment with surface decoration functions can be mounted on the façade.

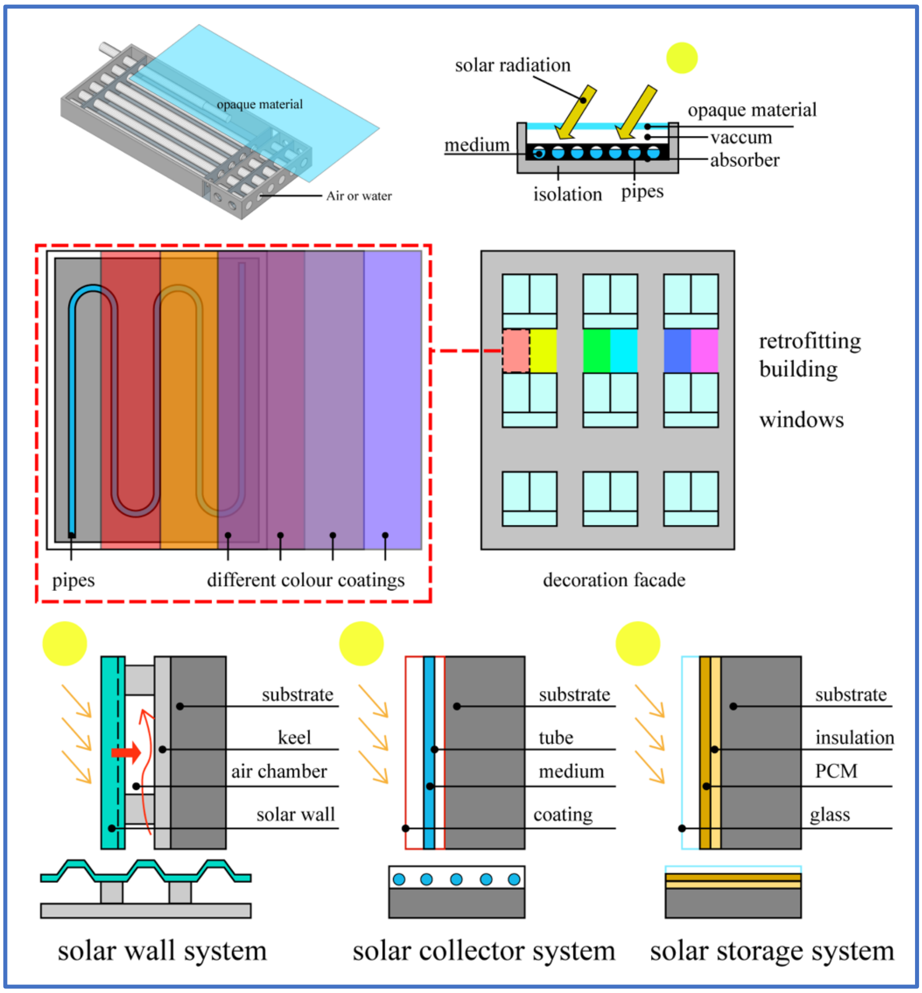


Figure 23 Summary of the solar collector construction

[Image by Author]

5.2.1.1.4 PVT

PVT Solar Panel: PVT refers to a combined system that integrates both photovoltaic and thermal generation. The transparency feature of the photovoltaic cells enables this hybrid functionality.

Construction: Common Features in Ventilation Module Façades

• PVT systems can be classified into two types: air-based and tube-based, depending on the medium used behind the photovoltaic cells.

• To enhance the efficiency of the photovoltaic unit, it's crucial to reduce its temperature. Using heat-transfer mediums, such as air or water, behind the photovoltaic cells helps lower their temperature and improves overall system efficiency.

• Additionally, using special surface coatings to reduce reflection losses can significantly increase photovoltaic efficiency.

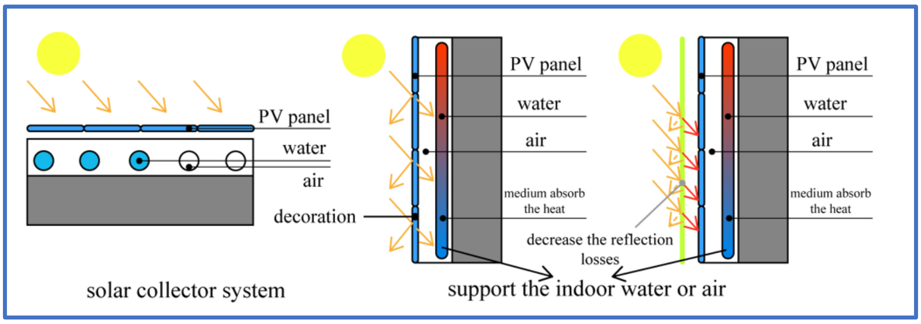


Figure 24 Summary of the PVT

[Image by Author]

5.2.1.1.5 Photovoltaic

The solar photovoltaic system is a facility that converts solar energy into direct current power through the photovoltaic effect of semiconductor materials. A solar cell is a device that converts light into electricity. Photovoltaic power generation is a technology that directly converts light energy into electricity by utilizing the photovoltaic effect at the interface of semiconductors. Based on the investigation of the above projects, the following conclusions can be drawn regarding different aspects of photovoltaic technology:

Construction: Common Features in Ventilation Module Façades

• Photovoltaic panels are not restricted to the building outline; they can be installed on the roof or façade, with only the solar exposure position needing consideration.

• The photovoltaic method is also not limited by roof shape, whether flat or sloped, due to flexible support structures.

• Since photovoltaic components are independent structures, they can easily be integrated into modular façade units. Therefore, it is recommended to use this method whenever possible in modular façade retrofitting projects.

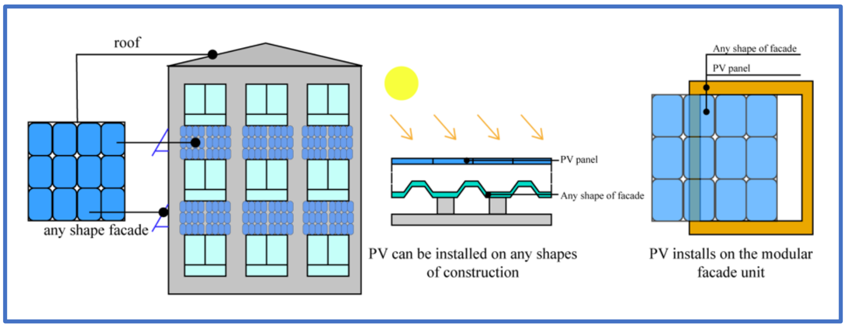


Figure 25 Summary of photovoltaic construction

[Image by Author]

5.2.1.1.6 Geothermal Energy

Geothermal Energy is a secondary energy source from the soil that absorbs and stores solar energy. Only three projects have adopted this technology, and the following conclusions can be drawn:

Construction: Common Features in Ventilation Module Façades

• To maximize geothermal energy use, corresponding tubes can be integrated into the façade unit. These tubes can be covered with insulation material to prevent heat loss.

Purposes: Single-Purpose or Multi-Purpose

• Geothermal heat pump technology can be combined with other solar-related techniques, such as façade solar collectors, to complement each other and improve overall efficiency.

Work Principle: Basic Working Principle

• Geothermal energy harvesting relies on solar energy. It is most effective in areas with abundant solar resources. The sun heats the ground, and the soil, acting as a phase change material, stores this solar energy. Geothermal equipment then transfers the heat through tubes to provide heating for the building.

5.2.1.1.7 Solar Lighting

The smart lighting system utilizes solar light directly through reflective equipment. Only one project has adopted this method due to its high cost. As a non-electric lighting system, buildings using this technology can rely on sunlight for indoor lighting during the day, reducing electricity consumption for lighting.

5.2.1.2 Technologies in Case Studies and the Attributes Implications

Through an in-depth analysis of Horizon 2020 building envelope retrofit cases, this study identifies seven core renewable energy and energy-efficient technologies: smart ventilation systems, dynamic shading devices, solar thermal collectors, photovoltaic-thermal (PVT) systems, photovoltaics (PV), geothermal heat pumps, and solar lighting systems**.**

The application of these technologies significantly shapes diverse attributes of retrofit solutions across the following dimensions:

1. **Thermal Performance**:
   - PVT systems combined with high-performance insulation (e.g., U-value improvement from 1.8 to 0.25 W/m²K in the MEEFS project) reduce heat flux by 60% (MEEFS RETROFITTING, 2012).
   - Geothermal heat pumps (e.g., RenoZEB project) stabilize indoor temperature fluctuations (±1.5°C) using underground thermal stability. (RenoZEB, 2017)
2. **Energy Efficiency**:

- PV integration with dynamic shading (e.g., BRESAER) reduces summer cooling loads by 40% while enhancing winter solar gain by 25%. (BRESEAR, 2015)
- The combined energy storage systems (e.g., PLUG-N-HARVEST) cut artificial lighting energy use by 70% via fibre-optic daylight transmission. (PLUG-N-HARVEST, 2017)

3. **Cost and Timeline**:
   - Prefabricated facade modules (e.g., BERTIM) shorten construction timelines by 50% but increase costs by 15% (€80/m²). (BERTIM, 2015)
   - Standardized solar thermal collectors (e.g., 4RinEU) reduce costs to €45/m² through economies of scale, with a lifecycle payback period ≤8 years. (4RinEU, 2016)
4. **Spatial and Operational Adaptability**:
   - Dynamic shading devices (e.g., ADAPTIWALL) support multi-mode operation ("shading-daylighting-power generation"), adapting to diverse climates and building orientations. (ADAPTIWALL, 2013)

This study analysed those selected cases from H2020 and extracted available parameters for horizontal comparison (please see Appendix A), which were encoded as key weighted attributes in the CBR decision-making tool. By quantifying the performance boundaries and implementation constraints of the technology combination, the CBR model can achieve modular retrofit strategy matching.

The next section introduces the data source and the normalization methods of these attributes. A dynamic weight distribution model based on the Analytic Hierarchy Process (AHP)- entropy method was established, ensuring the scientific and transparency of the multi-objective optimization of the CBR tool.

5.3 Demonstration of the Prototype for CBR Decision-making Support

5.3.1 Case Attributes

The case attributes derived from Horizon 2020 retrofits form the backbone of the CBR model's decision logic. To achieving the CBR (Case-Based Reasoning) function, it is essential to determine the attributes for each case. Since attributes can vary widely, different assessment solutions are implemented to measure case performance. These attributes, rigorously quantified and structured in the database, are not merely static data points but dynamic criteria of modular retrofits.

5.3.1.1 Classification Attributes/Inputs:

Classification attributes refer to the categorized characteristics of case buildings. In Liu et al.,'s research, they defined those type of attributes as "Classification" (Liu, et al., 2024). In Zhao et al.,'s research, they defined the name as "First-Layer Attributes" (Zhao, et al., 2019). Those attributes are for users' input, which describe the discrete properties that are not numerical in nature.

This study researched and analysed the cases from Table 9. Based on the analysis information of case studies (shown in Appendix A), the classification attributes/inputs for users are summarized into 4 categories: Duration, Cost, Complexity, Energy Performance. (Shown in Table 10)

Table 9 Nomenclature in CBR

Abbreviation	Representative in CBR
4RinEU (4RinEU, 2016)	Case 1
A2PBEER (A2pbeer, 2013)	Case 2
ADAPTIWALL (ADAPTIWALL, 2013)	Case 3
BERTIM (BERTIM, 2015)	Case 4
BRESAER (BRESEAR, 2015)	Case 5
BuildHEAT (BuildHEART, 2015)	Case 6
E2VENT (E2VENT, 2015)	Case 7
EnergyMatching (EnergyMatching, 2017)	Case 8
Envision (Envision, 2017)	Case 9
HEART (HEART, 2017)	Case 10
Heat4Cool (Heat4cool, 2016)	Case 11
HERB (HERB, 2012)	Case 12
ImPRESS (ImPRESS, 2015)	Case 13
INSPIRE (INSPIRE, 2012)	Case 14
MEEFS RETROFITTING (MEEFS RETROFITTING, 2012)	Case 15
MF-RETROFIT (MF-Retrofit, 2013)	Case 16
MORE-CONNECT (MORE-CONNECT, 2014)	Case 17
PLUG-N-HARVEST (PLUG-N-HARVEST, 2017)	Case 18
Pro-GET-OnE (Pro-Get-One, 2017)	Case 19
ReCO2ST (ReCOST2T, 2018)	Case 20
REnnovates (REnnovates, 2015)	Case 21
RenoZEB (RenoZEB, 2017)	Case 22
RETROKIT (RETROKIT, 2012)	Case 23

Table 10 Classification/Inputs and its related Attributes

Classification/Inputs	Related Attributes
Duration	On-site Construction
	Total Period
Cost	Cost for the project
Complexity	Prefabricated/On-site
	Replicable
	Installation place
Energy Performance	Material/Construction Structure
	Energy Saving
	Payback Time

How to determine the importance among these "Related Attributes" requires experts to determine the weight.

Scope for Demonstration: Due to this study is PhD research, which there is no participation of experts. To make this prototype work, the input range will adopt the average value here. If encountering the fuzzy part (e.g., if there is no relevant information can be accessed from the case report), it is regarded as a fuzzy attributes, and the overall classification will be calculated based on the average score. Further discuss of Fuzzy attribute is followed in 5.3.1.1.5.

5.3.1.1.1 Duration

"Duration" is calculated based on the on-site construction time and the total period of the project and the quantity units of all parameters are months. As shown in

Table 11, the total period of each project is clearly indicated. This can be obtained not only from their project reports but also from the links of each project on the H2020 official website. However, more than half of these projects do not have clear reports on the on-site construction time. Even for those projects that have reported on-site construction times, their descriptions were recorded in different ways. Therefore, these 2 attributes were calculated in program. As mentioned previously in the Scope for Demonstration in 5.3.1.1, the weights of each attribute were set equally to get the average value for input – this strategy is applied to the fuzzy calculation of the remaining attributes in the following sub-sections.

Table 11 Duration of All Cases from Database

	Duration (Month)		**Fuzzy Calculation**
	On-site Construction	**Total Period**	**Input**
Case1	0.5 (2weeks)	57	Very High
Case2	N/A	54	High
Case3	2 (prototype)	48	Medium
Case4	N/A	48	Medium
Case5	N/A	54	High
Case6	N/A	54	High
Case7	units on the external wall - 1-2days BEMs unit - 1 m2 of E2VENT ventilated facade - 80 minutes/1 worker	42	Low
Case8	N/A	58	Very High
Case9	Less than 4 (report shows “in a semester”)	63	Very High
Case10	2	58	Very High
Case11	N/A	54	High
Case12	N/A	42	Low
Case13	N/A	48	Medium

Case14	N/A	48	Medium
Case15	3（based on installed facade)	60	Very High
Case16	N/A	42	Low
Case17	N/A	54	High
Case18	near 3 (spring-summer)	63	Very High
Case19	N/A	65	Very High
Case20	3 (most completed in summer, but one delayed by Covid-19)	48	Medium
Case21	N/A	36	Very Low
Case22	N/A	52	High
Case23	N/A	48	Medium

5.3.1.1.2 Cost

The classification of Cost is straight-forward, which can be obtained directly from the projects' reports, shown in Table 12. For setting the range of Input, the strategy is to take the average of these data.

- Very Low: Under 4 million €
- Low: 4 million € -- 6 million €
- Medium: 6 million € -- 8 million €
- High: 8 million € -- 10 million €
- Very High: Above 10 million €

Table 12 Cost of All Cases from Database

	Cost	Input
Case1	€ 4 597 455	Low
Case2	€ 10 259 963	Very High
Case3	€ 4 994 795	Low
Case4	€ 4 914 210	Low
Case5	€ 5 849 107	Low
Case6	€ 9 050 448	High
Case7	€ 3 402 789	Very Low
Case8	€ 6 926 301	Medium

Case9	€ 5 981 316	Low
Case10	€ 6 638 688	Medium
Case11	€ 7 934 578	Medium
Case12	€ 8 606 893	High
Case13	€ 6 041 474	Medium
Case14	€ 10 841 678	Very High
Case15	€ 9 934 577	High
Case16	€ 5 038 667	Low
Case17	€ 5 634 811	Low
Case18	€ 6 860 026	Medium
Case19	€ 4 975 339	Low
Case20	€ 8 323 209	High
Case21	€ 6 847 730	Medium
Case22	€ 8 708 052	High
Case23	€ 9 969 768	High

5.3.1.1.3 Complexity

The Complexity for construction is calculated based on whether it is prefabricated or need on-site construction, if it is replicable, and the installation place. As shown in , and fuzzy calculations are performed on the input.

Table 13, these attributes could not be compared in parallel, and fuzzy calculations are performed on the input.

Table 13 Complexity for Construction of All Cases from Database

	Complexity (for Construction)			Fuzzy Calculation
	Prefab/On-site	Replicable	Installation place	Input
Case1	technology concepts and business models	N/A	N/A	Low
Case2	On-site Retrofitting	N/A	Windows, Façade, insulation panels	High
Case3	On-site Retrofitting	N/A	Façade, wall system	Medium

Case4	On-site Retrofitting	N/A	Facades	Medium
Case5	On-site Retrofitting	easy assembly and disassembly	Windows, Façade, Insulation panels	Low
Case6	On-site Retrofitting	N/A	Facades	Very High
Case7	On-site Retrofitting	N/A	N/A	High
Case8	On-site Retrofitting	N/A	Envelope, Windows	Very High
Case9	On-site Retrofitting	easy assembly	Envelope (facades and roofs)	Low
Case10	On-site Retrofitting(toolkit)	N/A	Envelope, Windows	High
Case11	On-site Retrofitting	easy assembly	N/A	Low
Case12	On-site Retrofitting (Computer model)	N/A	Envelope (facades and windows)	Low
Case13	prefabricated	easy assembly	Exterior prefabricated concrete panels	Low
Case14	prefabricated	easy assembly	Envelope (a new high performance prefabricated timber envelope around the building, integrated with multi-systems)	Low
Case15	prefabricated: Standardised dimensions for panels and modules	Low maintenance, easy assembly, and disassembly	Façade system	Low
Case16	On-site Retrofitting	easy assembly	facades	Low
Case17	prefabricated(customized)	easy assembly	Envelope(roof)	Low
Case18	On-site Retrofitting	N/A	Façade	Low
Case19	prefabricated	easy assembly	Envelope, Shell	Low
Case20	On-site Retrofitting: customizable model with a visual system	N/A	Windows, Façade, Insulation panels	Very High
Case21	prefabricated: Energy Module	Low maintenance, easy assembly	N/A	Low
Case22	On-site Retrofitting	easy assembly	N/A	Medium
Case23	half-prefabricated	easy assembly	facades, windows	Low

5.3.1.1.4 Energy Performance

Energy Performance is calculated upon the material and construction structure, energy saving and payback time. As shown in Table 14, fuzzy calculation is also applied for this input.

Table 14 Energy Performance for All Cases from Database

	Energy Performance			Fuzzy Calculation
	Material/Construction Structure	**Energy Saving**	**Payback time**	**Input**
Case1	prefabricated timber facades	60%-70%;	15% reduction of life cycle costs over 30 years	High
Case2	insulation layer façade, VIP,	50%	7 years	Medium
Case3	lightweight concrete, adaptable polymer materials, total heat exchanger	65%	14 years	High
Case4	timber facades	50%	N/A	Medium
Case5	fibre reinforced concrete	76.40%	N/A	Very High
Case6	PV inverter, metal substructure façade, ICT infrastructure	63%-71%;	N/A	Very High
Case7	phase change materials	70% Energy savings of more than 40%, Typical performance target of less than 25 kWh/m 2 year (excluding appliances)	N/A	Very High
Case8	N/A	70%	N/A	Very High

Case 9	new solar heat collectors in facade, heat harvesting ventilated glass	75%	N/A	Very High
Case10	DC heat pump, thermal storage, smart fan-coil, MIMO converter, façade panels, PV tiles, IoT devices and components for windows retrofit.	80%-90%;	⩽15 years	Very High
Case11	integration of RES (PV and Solar thermal)	20%-30%;	< 10 years	Very Low
Case12	PCM, VIPs, PV façade, LED lamps and light pipes	⩾ 80%;	2-5 years	Very High
Case13	polyurethane pane, lightweight pre-cast concrete, Phase Change Material	the recladding panels:8% per year; Hypucem panels: the U-Value of the external walls would reduce from 1.54 to 0.19 W/m2K; Severin demonstrator: energy saving 22% per year; potential time savings: 30%	N/A	Very Low
Case14	façade-integrated micro heat pump, wooden-frame envelope modules, mechanical ventilation unit	an overall Primary Energy consumption of the building lower than 50 kWh/m²/year.	N/A	Very High
Case15	thermoplastic polymers composite materials	up to 60%	less than 7 years	High
Case16	clay aerogel, PCMs, fly ash, FRP, organic combustible plasticizer	N/A	N/A	Medium
Case17	N/A	N/A	⩽8years	Medium
Case18	PnH double façade	N/A	<10years	Medium
Case19	timber-based components, aluminium windows, PV, and solar panels	88%	N/A	Very High
Case20	VIP, CPV, PCMs, The Cooling evaporative Kit	71%-90%	less than 15 years	Very High
Case21	N/A	60%	N/A	High

Case22	Modular “plug and play” facades	⩾60%;	⩽15 years	Very High
Case23	semi-industrial coatings	N/A	7 years	Medium

5.3.1.1.5 Fuzzy Attributes:

Fuzzy attributes represent properties that are more difficult to assess quantitatively, making them significant for many cases. Since it is often challenging for clients to provide precise quantitative requirements, fuzzy evaluation offers a simplified method for measuring customer demand. In terms of the operation of this prototype, the uncertain information (e.g., The parameters extracted for parallel comparison were not reported in some case studies—some case has detailed explanation, but some is N/A; or information is described in word by different authors from different research) could be considered fuzzy attributes.

As Zhao, et al. mentioned in their research, the trapezoidal membership function was the common way of the method for evaluating fuzzy attributes (Zhao, et al., 2019), which indicates the performance scores for various fuzzy term conditions.

Figure 26 presents the trapezoidal membership function, refers to Zhao, et al.’s publication at page 6 (Zhao, et al., 2019). Each fuzzy term input by users is converted into a corresponding membership value. After calculation in program, the input is shown in Table 16.

Table 15 Score condition for fuzzy term

[Concept adapted from (Zhao, et al., 2019)]

Fuzzy Term	Sore Intervals
Very Low	0-19
Low	20-39
Medium	40-59
High	60-79
Very High	80-100

Table 16 Fuzzy Range for All Cases from Database

	Input		Input
Case1	low	Case13	medium
Case2	low	Case14	low
Case3	low	Case15	low
Case4	high	Case16	high
Case5	low	Case17	high
Case6	medium	Case18	low
Case7	medium	Case19	medium
Case8	very high	Case20	low
Case 9	low	Case21	high
Case10	low	Case22	Low
Case11	low	Case23	very low
Case12	low		

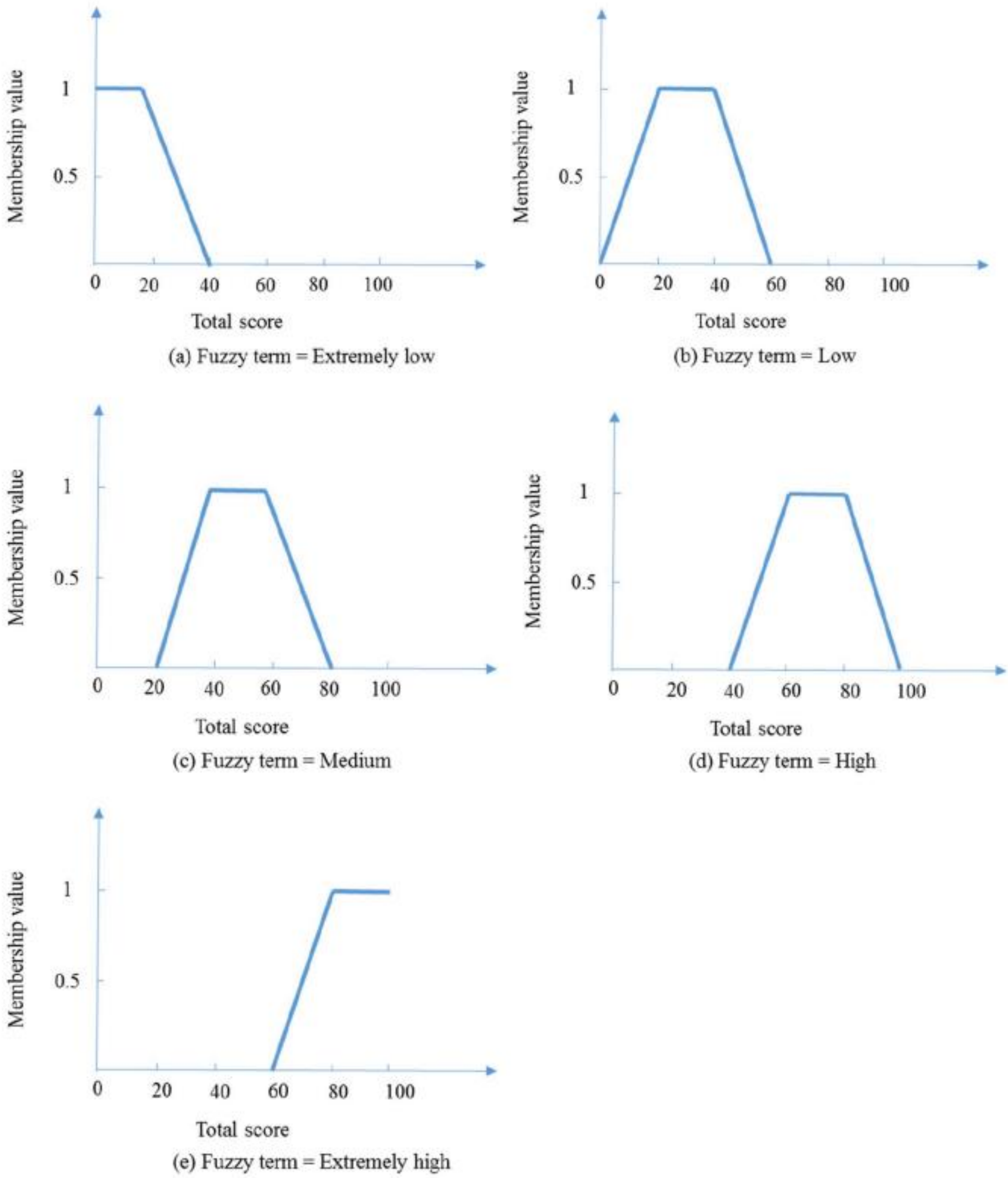


Figure 26 Trapezoidal membership function

[From: (Zhao, et al., 2019)]

5.3.2 Demonstration of Hypothetical Case

For instance, the hypothetical case is a low-rise residential building that aims to finish the project in around 4 years and the estimated budget for the project is at 5 million € maximum. With the limited budget, the clients would expect the module retrofit has a low complexity but achieving a very high energy performance, on this basis, it allows very high fuzzy range.

The first step: According to the fuzzy calculated range from CBR program (shown in Table 17), the user's input is determined in Table 18.

Table 17 Fuzzy Calculated Range from CBR Program

	Very Low	Low	Medium	High	Very High
Duration (Month)	＜40	40~45	45~50	50-55	＞55
Cost (Million, €)	＜ 4	4-6	6-8	8-10	＞10
Complexity Score	＜ 3	3-4	4.1-5	5.1-6	＞6
Energy Performance Score	＜ 4	4-4.9	5-5.9	6-6.9	＞6.9

Table 18 User's Input for the Hypothetical Case

Duration	Cost	Complexity	Energy Performance	Fuzzy Evaluation
Medium	Low	Low	Very High	Very High

The second step: The user proposes the priority for these 5 inputs as:

"Energy performance＞Complexity＞Cost＞Duration＞Fuzzy evaluation"

It is worth noting that in actual situations, determining the weight ratio relationship among the attributes in AHP typically relies on the judgment of experts. This has been discussed by Cui et al. (Cui, et al., 2024) that experts use their experience to make subjective pairwise comparisons of indicators, translating them into numerical values on a 1-to-9 scale to establish a judgment matrix, which then mathematically derives the weights. This subjective element is a key feature of AHP, integrating professional insights to ensure the rationality and precision of the evaluation. This judgment matrix is constructed using the 1-9 scaling method proposed by Saaty in 1994. (Saaty, 1994; Saaty, 2008).

Given that this is a hypothetical case, the weight ratio in here will be determined by the average multiple ratios.

The third step: Case retrieval. Based on the user’s input options and weight priorities, the CBR program sorting cases by AHP algorithm to achieve case retrieval. Coding is attached in Appendix B.

The calculation for this hypothetical case is shown in Table 19 & Table 20.

Table 19 Calculation of Matching Cases by AHP

	Duration	Cost	Complexity	Energy Performance	Fuzzy Evaluation
case 1	0.271964	0.131024	0.122398	0.201262	0.149906
case 2	0.217571	0.327561	0.244796	0.150946	0.149906
case 3	0.163178	0.131024	0.183597	0.201262	0.149906
case 4	0.163178	0.131024	0.183597	0.150946	0.299813

case 5	0.217571	0.131024	0.122398	0.251577	0.149906
case 6	0.217571	0.262049	0.305995	0.251577	0.22486
case 7	0.108786	0.065512	0.244796	0.251577	0.22486
case 8	0.271964	0.196537	0.305995	0.251577	0.374766
case 9	0.271964	0.131024	0.122398	0.251577	0.149906
case 10	0.271964	0.196537	0.305995	0.251577	0.149906
case 11	0.217571	0.196537	0.244796	0.050315	0.149906
case 12	0.108786	0.262049	0.305995	0.251577	0.149906
case 13	0.163178	0.196537	0.122398	0.050315	0.22486
case 14	0.163178	0.327561	0.244796	0.251577	0.149906
case 15	0.271964	0.262049	0.122398	0.201262	0.149906
case 16	0.108786	0.131024	0.122398	0.150946	0.299813
case 17	0.217571	0.131024	0.122398	0.150946	0.299813
case 18	0.271964	0.196537	0.122398	0.150946	0.149906
case 19	0.271964	0.131024	0.122398	0.251577	0.22486
case 20	0.163178	0.262049	0.305995	0.251577	0.149906
case 21	0.054393	0.196537	0.122398	0.201262	0.299813
case 22	0.217571	0.262049	0.244796	0.251577	0.149906
case 23	0.163178	0.262049	0.122398	0.150946	0.074953

Table 20 Ranking of Matching Cases by AHP

	The degree of proximity to the positive ideal solution (A+)	**The degree of proximity to the negative ideal solution (A-)**	**Comprehensive score index**	**Ranking**
case 1	0.126933	0.164897	0.565045	13
case 2	0.065533	0.185019	0.738444	3
case 3	0.140725	0.096696	0.407276	20
case 4	0.137273	0.099916	0.421251	19
case 5	0.132195	0.132835	0.501207	17
case 6	0.057961	0.177197	0.753523	1
case 7	0.180755	0.082452	0.313258	22
case 8	0.06656	0.196786	0.747251	2
case 9	0.126288	0.168328	0.571347	12
case 10	0.077854	0.189753	0.709073	5
case 11	0.103368	0.142435	0.579468	11
case 12	0.128381	0.136525	0.515372	14
case 13	0.135003	0.106128	0.440126	18
case 14	0.090677	0.168988	0.650792	7
case 15	0.085155	0.189872	0.690377	6
case 16	0.169986	0.070135	0.292082	23
case 17	0.129148	0.130901	0.503371	16
case 18	0.105186	0.172328	0.620971	8

case 19	0.122648	0.169935	0.58081	10
case 20	0.094057	0.152382	0.618336	9
case 21	0.183184	0.086783	0.321458	21
case 22	0.068912	0.168638	0.709905	4
case 23	0.122955	0.129343	0.512659	15

From the ranking results in

Table 20, the most matching case is Case 6, which is BuildHEAT (BuildHEART, 2015) (listed in Table 9). BuildHEAT is an affordable retrofit solutions' toolkit, it suggests a combined system of PV module with geothermal energy (shown in Table 8 & Figure 27). The more detailed suggestion is discussed in 5.2.1.1, solar photovoltaic (PV) systems and geothermal heat pumps can be effectively combined for a more sustainable and efficient energy solution. The PV system generates electricity from sunlight to power the geothermal heat pump, while the heat pump utilizes the stable underground temperatures to efficiently heat and cool a building. By using the building's own electrical output to power the geothermal system, these technologies reduce reliance on conventional energy sources, increase self-sufficiency, and lower energy costs. And the independent and flexible support structure of PV can be easily integrated into modular panel units, not restricted by the shape of the building's appearance.

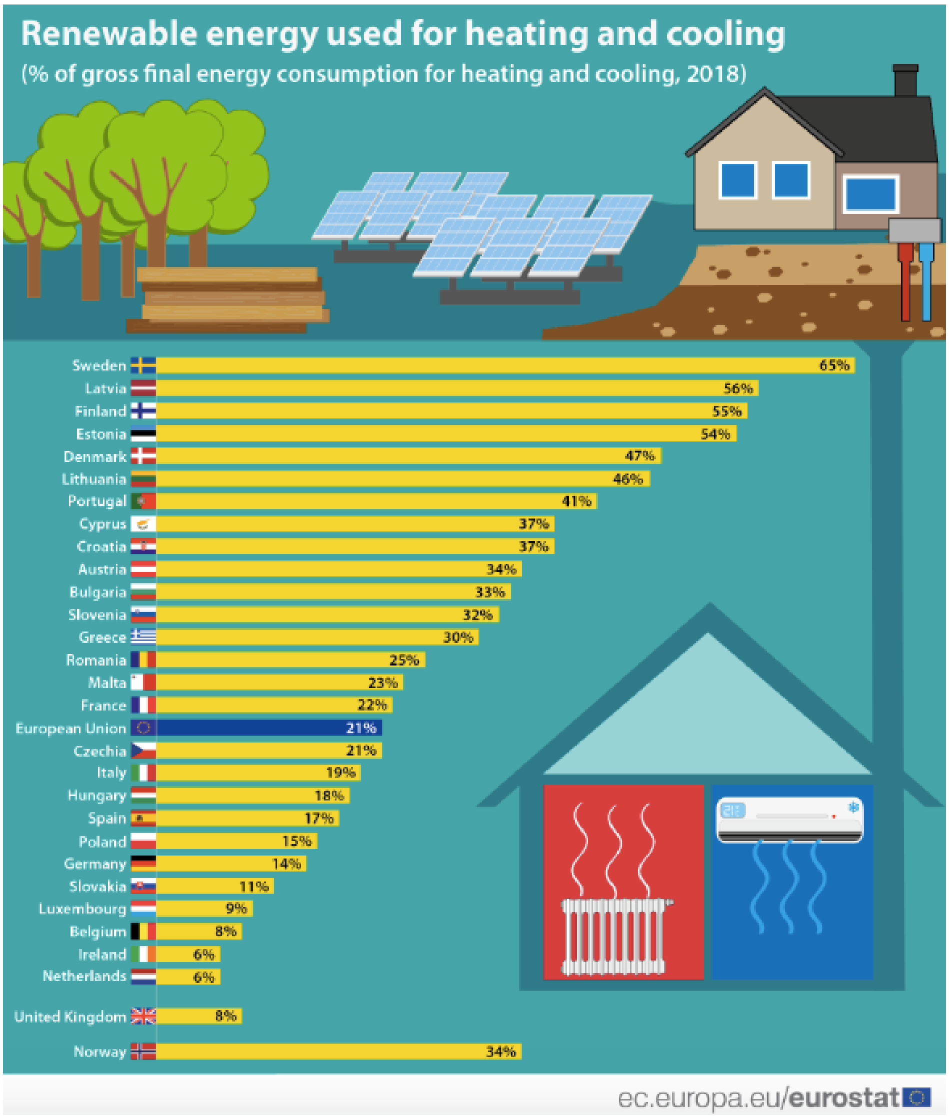


Figure 27 Retrofit Suggestion by BuildHEAT

[From: (BuildHEART, 2015)]

In the similar research done by other research team, their outcomes stop at this stage. Such as Liu et al.'s outcome is just presenting the 2 most matching cases (Liu, et al., 2024). Zhao et al.'s outcome listed in page 9 of their publication as

"Reference cases 58, 23: Double-glazing of existing windows" (Zhao, et al., 2019)

This study provides users with further research information. For the suggested strategy of PV based on this hypothetical case, the reference cost for different cases in terms of PV panel in Table 21 can be referred to by users.

In addition, this study also analysed the structural layers of the module, to provide users, who is not from architectural background, with a more intuitive understanding. This will be further discussed in next section 5.3.3.

Table 21 Reference cost for different cases in terms of PV panel

Manufacturer	Model Number	Price	Model Configuration (WP)	Average price per power (EUR/W)
Maxeon Solar Technologies Ltd	SPR-MAX3-415 1812x1046x40	£667.21	0.415	£ 1,607.73
Solarday	PX60-280 (60 Cells)	£121.23	0.28	£ 432.98
Solarday	PX72-330 (72 Cells)	£139.63	0.33	£ 423.12
Solarday	SDM60-300 (60 Cells M2 Mono)	£344.47	0.3	£ 1,148.24
Solarday	XMP60-305 (60 Cells M4 Mono)	£334.44	0.305	£ 1,096.52
Peimar S.r.L.	SM325M	£158.88	0.325	£ 488.87
Peimar S.r.L.	SM330M	£192.14	0.33	£ 582.23
Peimar S.r.L.	SM400M	£147.80	0.4	£ 369.49
Sharp Electronics GmbH	NU-JC410 (1722*1134*35 mm)	£209.03	0.41	£ 509.82
Sharp Electronics GmbH	NU-JC405B (1722*1134*35 mm)	£144.67	0.405	£ 357.21
Sharp Electronics GmbH	NU-JD445 (2108*1048*35 mm)	£194.65	0.445	£ 437.42
Jinzhou Yangguang Energy Co., Ltd	JMPV-TV2/54-550(R) (1960*1303*35 mm)	£84.76	0.55	£ 154.12

Jinzhou Yangguang Energy Co., Ltd	JMPV-TV2/48-465(R) (1748*1303*35 mm)	£67.35	0.465	£ 144.83
Jinzhou Yangguang Energy Co., Ltd	JMPV-TV2/48-490(R) (1748*1303*35 mm)	£70.09	0.49	£ 143.04
Trina Solar Co., Ltd.	TSM-490DE18M.08(II) 2176x1098x35	£210.93	0.49	£ 430.47
Trina Solar Co., Ltd.	TSM-500DE18M.08(II) 2176x1098x35	£270.14	0.5	£ 540.27
Trina Solar Co., Ltd.	TSM-520DE18M.08(II) 2176x1098x35	£292.34	0.52	£ 562.20
Chint Solar (Zhejiang) Co., Ltd.	CHSM60M-HC-365 1755x1038x35	£255.85	0.365	£ 700.95
Chint Solar (Zhejiang) Co., Ltd.	CHSM60M-HC-380 1755x1038x35	£265.88	0.38	£ 699.68
Chint Solar (Zhejiang) Co., Ltd.	CHSM54M-HC-400 1708x1133x30	£652.16	0.4	£ 1,630.40

5.3.3 Potential Construction Suggestions

As those analysed cases from H2020 (in Table 7) all differ in the details of module design, the construction has been simplified in this discussion. Illustration is based on a hypothetical module (in 1meter by 1meter).

The simplified module structure that can be summarized based on the reviewed case is shown in Figure 28. The structural concept of module is mainly explained here. The more detailed technical analysis of module is discussed in 5.2.1.1.

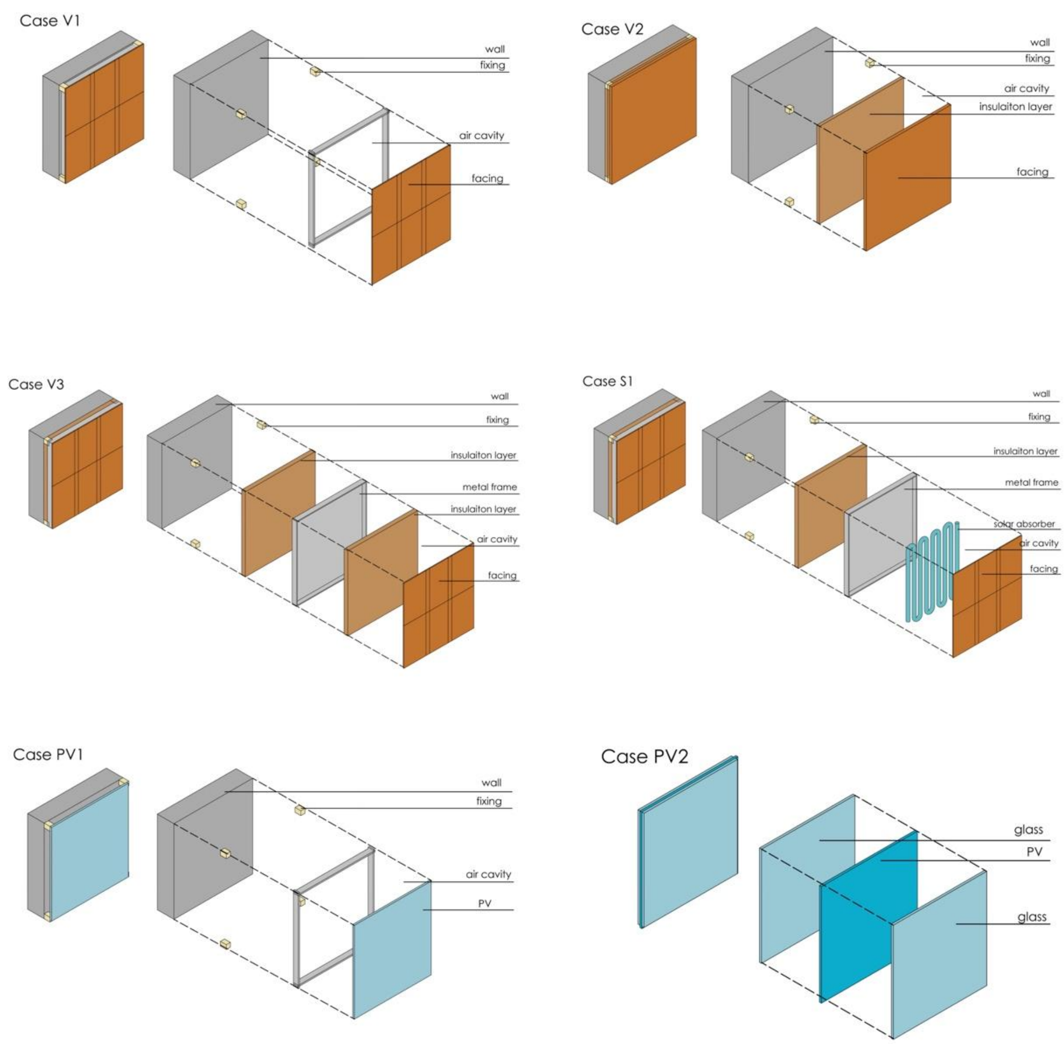


Figure 28 Summarized Simplified Module Structure from Reviewed Cases
[Image by Author]

Case V1 to V3 represent the ventilation system. V1 is the simplest approach as a metal frame is attached to the existing building surface with a facing layer attached on the outermost layer to create an air cavity in between, and this facing layer can combine with solar shading to open up. V2 is to add an insulation layer on the existing surface and form a cavity with the facing layer. V3, on the other hand, adds 2 insulation layers to each of existing surface and the facing layer, joint with a metal frame in between, which provides a dual-layer air cavity.

Case S1 represents the solar collector system, which has a similar structure with V3, by replacing the insulation layer next to the facing layer in V3 with a solar collector, and the facing layer for S1 usually use coating for better absorb efficiency.

Case PV1 and PV2 represent the Photovoltaic. The simplest construction is similar with V1 by just replacing the facing layer with the PV panel. PV2 is the glass-PV, where the PV panel in embedded between 2 glasses, this design is called as "glazing" (Omeiza, et al., 2024). This glass layer protects the internal components, reduces heat loss from the collector, and improves its overall performance by allowing sunlight in while minimizing convective and radiative heat escape. Glass-PV often used in combination with solar collector as well. As mentioned by Omeiza et al., some high-performance collectors may use tempered, low-iron glass with anti-reflective coatings to further increase transparency and efficiency (Omeiza, et al., 2024).

There are also different joint methods between each layer of the module units. Simplified concepts are summarized in Figure 29.

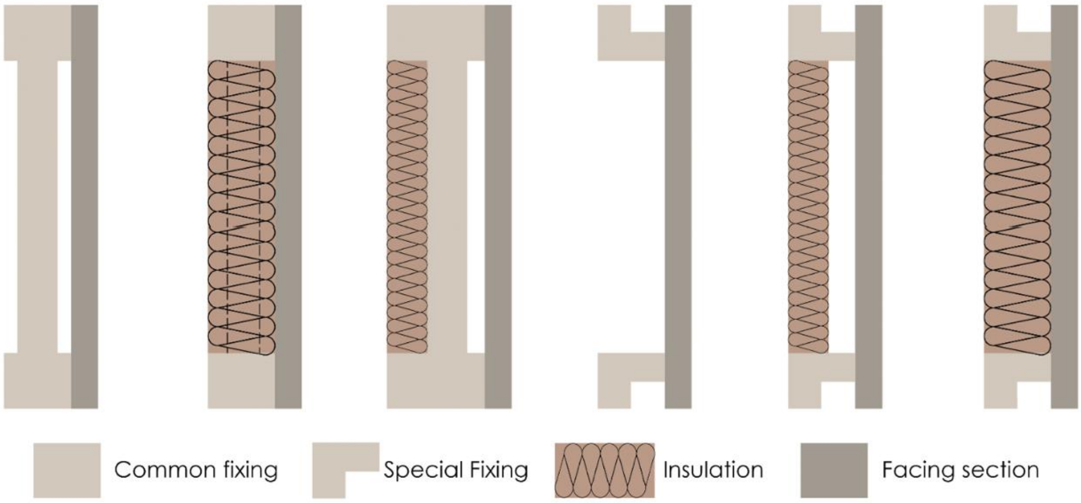


Figure 29 Joint Methods for Module

[Image by Author]

In Figure 30, the upper 4 units are the basic module components. “MP1” (Module Panel 1) is the construction Case V2 from Figure 28. The structure of V1 is too simple, while the dual insulation layers of V3 is relatively thick. Therefore, it is recommended to use V2 as a common suggestion. “MP2” (Module Panel 2) is the independent solar absorber unit, in Figure 28, Case S1 attaches this unit outside the insulation layer. PV is PV panel and GPV is Glass-PV panel.

The below 4 units in Figure 30 is the suggestion for the reorganized components. “A” suggests the insulation embedded in the frame of solar collector. “B” is adding the PV panel outside of the ventilation system with an insulation layer embedded. “C” is similar with “B”, but only replacing the PV to Glass-PV. “D” is combining the Glass-PV in the surface of solar collector.

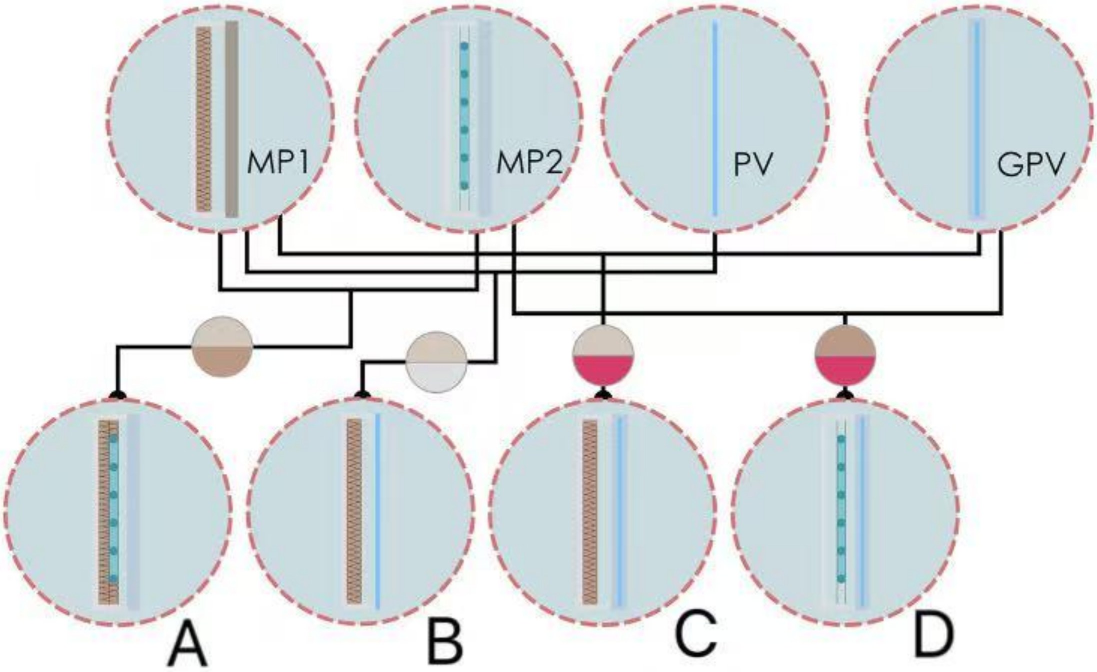


Figure 30 Suggestion for the Reorganized Components
[Image by Author]

After reorganized the Joint Methods for Module from Figure 29 and Suggestion for the Reorganized Components of Figure 30. The results reveal the potential construction layers of the module components, shown in Figure 31.

From the outcome of the hypothetical case demonstration in 5.3.2, which suggests the most matching solution is case 6, BuildHEAT (BuildHEART, 2015). And it has been mentioned in the previous section that the module strategy is a combined system of PV module with geothermal energy.

Thus, the potential construction of the model can be directly obtained from Figure 31: BI to BVI.

The main purpose of this step is to provide the user not only the descriptions of the most similar case, but also a straightforward idea of the related structural possibilities. Translating the knowledge simply to the users without a background in architecture.

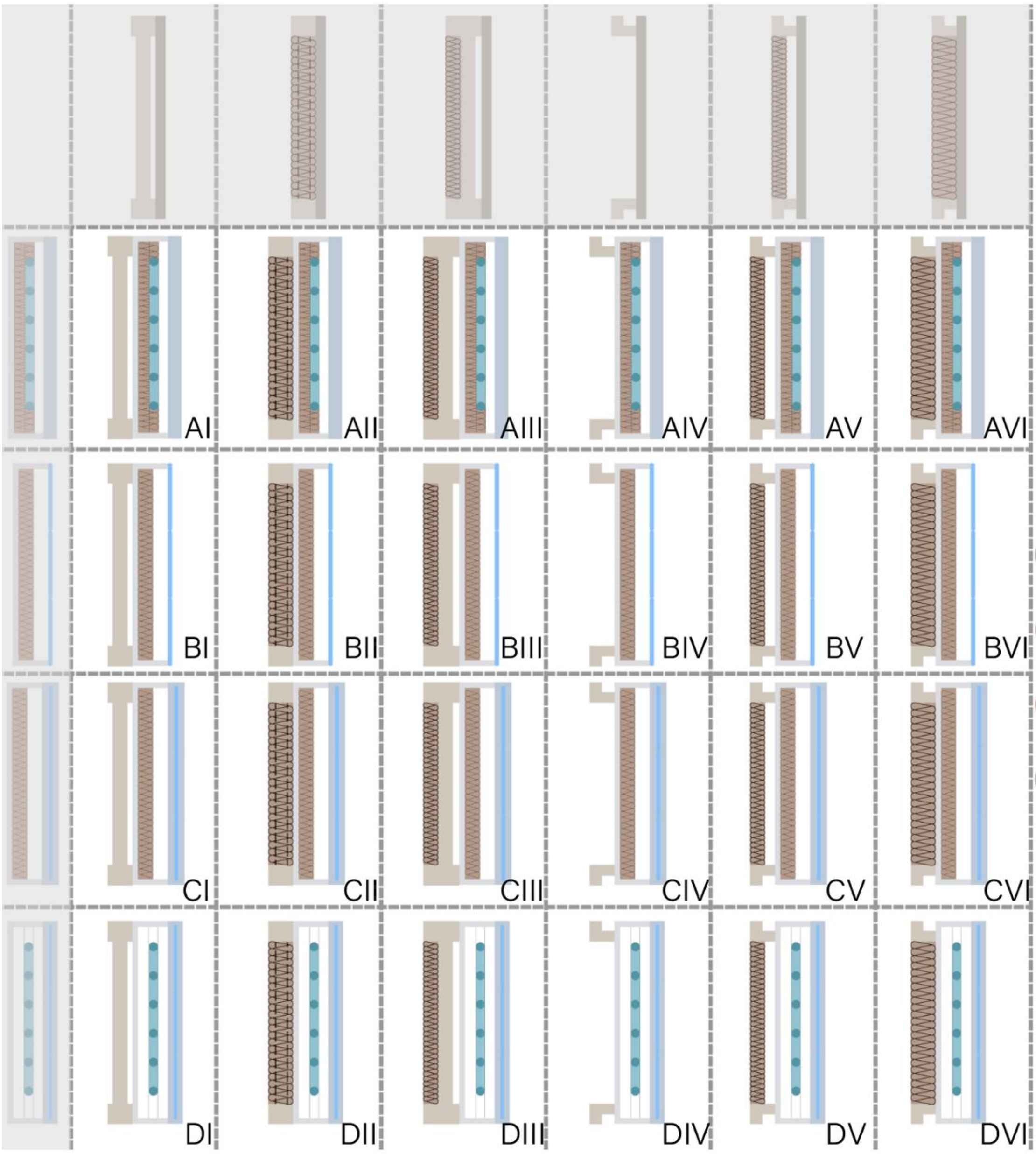


Figure 31 Potential Construction Layers of the Module Components

[Image by Author]

5.3.4 Interactive Interface

The interactive interface serves as a bridge between the database and the client's needs. The database should include detailed information about the performance of each building, which will be presented in tables. Users can make decisions based on these attributes and values. However, since the target customers are primarily homeowners, the interface should be simplified to reduce input difficulty. To achieve this, the interface should require only indicators that are familiar to users. Fuzzy performance indicators, rather than numerical values, are recommended to make the process more user-friendly.

In summary, the database contains detailed information for each case, while the interface presents fuzzy options for users to select. When customers input their preferences using these options, the corresponding case information will be displayed, including numerical values, construction diagrams, and other relevant attributes.

The interface is written in python and the algorithm used is AHP. The current stage of written codes can achieve a simple interface display, as shown in Figure 32. The interface code is open source and can be found in Appendix C.

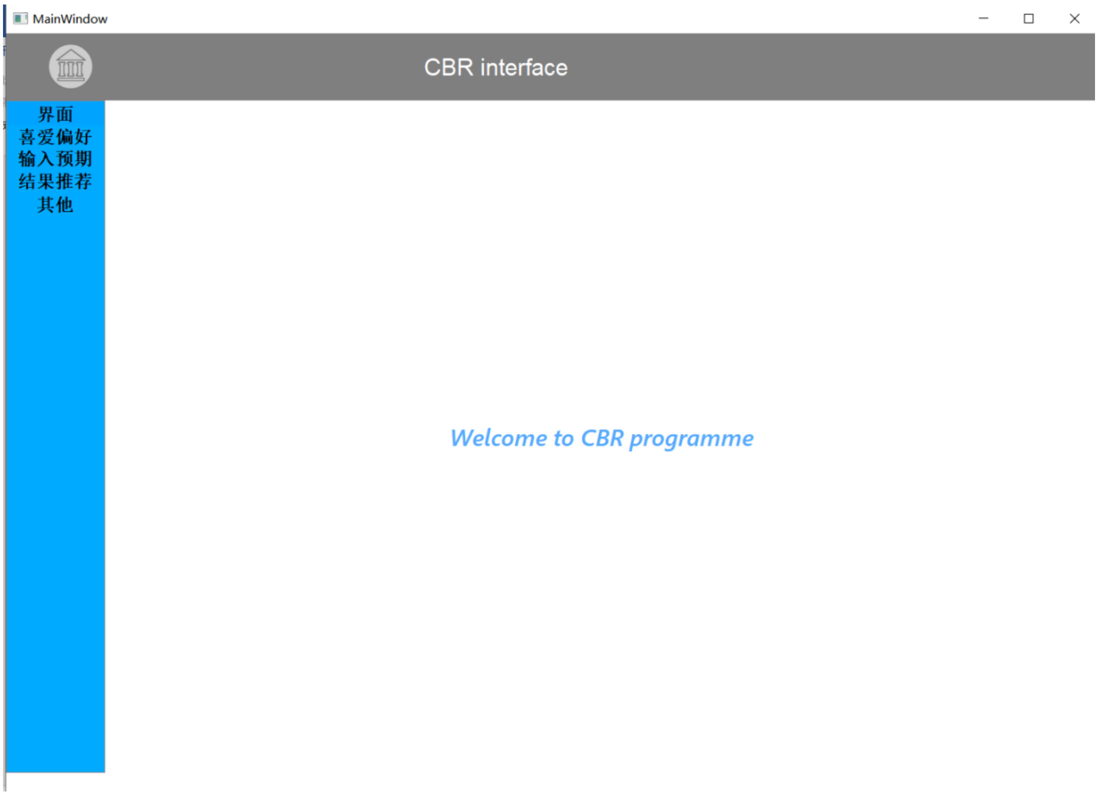


Figure 32 Interface Appearance

[Image by Author]

Data Input and Processing

- The AHP module loads the data from input.xlsx and Matrix.xlsx for quantification processing and matrix operation.
- The CBR module obtains the input properties from the user interface to generate the case feature vector.

Algorithm Calculation

- **AHP weight calculation:**

  - Based on the input matrix, the weight vector and the maximum eigenvalue are calculated, and consistency checked.

- **CBR similarity calculation:**

  - Global similarity was calculated by combining subjective (AHP) and objective (entropy weight) weights.

Results for the Presentation

- The calculated results are presented through tables and text boxes in the GUI.
- Generate Excel files to save the calculation results.

5.4 Summary

This chapter transitions from theoretical frameworks to practical implementation by developing a functional CBR prototype for modular retrofits, structured around three core components:

1. Case Study Analysis for Attributes

The analysis of case studies identifies and categorises modular retrofit technologies. By exploring and defining the construction of module in section layers, to summarise and analysis the high frequency associated combinations. Yet, the limitation exists in emerging technologies were underrepresented due to project timelines.

2. Case Attribute Setup

Extracting and normalise decision-critical attributes from fragmented case data. Based on this, a structured database enabling cross-case comparability and objective ranking.

3. User-Centric Interface Design

An interface is built in simplify technical complexity for non-expert users (e.g., homeowners). Thus, the fuzzy inputs that convert technical metrics have been made.

A demonstration of a hypothetical case is presented for this CBR prototype's practical application. Based on the potential demands input by users, the most similar cases were retrieved for reference. And a further study of the relevant potential building and factory product information is presented, so that users can have a better understanding. All research work of this study is open access and is listed in Appendix.

For the scope of this CBR prototype and its database, which requires the professional judgements from experts, such as determine the weight ratio among attributes, etc. This will be further discussed in next Chapter.

6 Discussion

6.1 Introduction

From Chapter 5, the prototype of CBR model is developed based on AHP algorithm. As AHP presents more advantages compared to other algorithm in this circumstance, which determines the criteria and priorities based on comparing weights. The consistency check during AHP calculation ensures rationality and the outcome would more rely on subjective judgment. From Chapter 2, section 2.5, the proper ways of evaluation have been discussed. According to that, the cross-validation with alternative methods drives a feasible scheme for evaluation. In the research from Dagdeviren, et al. (Dagdeviren, et al., 2009), an evaluation model based on AHP is developed. In their research, another solution of TOPSIS was used to evaluate and improve the AHP model, which reduced the error range of AHP calculation. This strategy of using TOPSIS can be borrowed to evaluate the prototype of CBR model from Chapter 5 as well. Shih et al. mentioned in their research, as TOPSIS is an improved group decision making method, which can solve the weight allocation problem in multi-person cooperative scenarios. (Shih, et al., 2007)

This chapter focuses on discussion the evaluation results by comparing the AHP algorithm with TOPSIS algorithm. Furthermore, the limitation of the CBR prototype will also be discussed.

6.2 Discussion of the Results

6.2.1 Verification of CBR-AHP model: Integration of Weightings via TOPSIS

AHP is to incorporate subjective expert opinions and priorities into the decision-making process. Although it requires the participation of experts to determine the judgements, it is subjectively more flexible and more suitable for small databases. While Entropy-Weighted Fuzzy TOPSIS is to objectively determine the weights of key performance indicators and provide a quantitative assessment of each basin. TOPSIS is computationally more efficient for complex problems with many alternatives and avoids rank reversal. Cui et al claimed that for even better accuracy, combining the strengths of both methods by using AHP for criteria weighting and TOPSIS for alternative ranking is a common and effective strategy. (Cui, et al., 2024)

The final weightings for TOPSIS are a combination of the subjective (AHP-derived) and objective (entropy-derived) weightings. By assigning appropriate importance to both methods, the combined weight of attribute j, denoted as ω_j^{final}, is calculated using a weighted average:

$$\omega_j^{final} = \alpha\omega_j^{AHP} + (1-\alpha)\omega_j^{Entropy} ,$$

where α represents the importance factor for subjective weights.

These integrated weights are subsequently used in the TOPSIS method to compute the relative closeness of each alternative to the ideal solution, guiding decision-making in a structured and balanced manner.

Table 20 represents a AHP analysis to evaluate multiple cases based on four criteria: Duration, Cost, Complexity, and Energy Efficiency. The criteria weights for each case have been determined using the AHP method, reflecting their relative importance in the decision-making process.

According to this, (A+) and (A-) represent the positive ideal solution (best case) and negative ideal solution (worst case), respectively, for each case based on the weighted criteria.

Similarity measures the relative closeness of a case to the positive ideal solution, calculated as

$$C^* = \frac{D^-}{D^+ + D^-}$$

where D^{+} and D^{-} are the distances to the positive and negative ideal solutions, respectively. The Sort column ranks the cases based on their similarity scores, with lower ranks indicating better performance.

According to the AHP calculation, Case 6 achieves the best performance with the highest similarity score of 0.753 and is ranked 1st, shown in Table 20. Case 8, Case 2 and Case 22 follow with high similarity scores, making them strong candidates for selection. Cases like Case 16 (0.292), Case 7 (0.0.313), and Case 21 (0.321) have low similarity scores, indicating poor alignment with the ideal solution. This analysis enables stakeholders to prioritize cases that best meet the evaluation criteria, focusing on those ranked highest in the Sort column.

Table 22 Ranking of Matching Cases by TOPSIS

	The degree of proximity to the positive ideal solution (A+)	**The degree of proximity to the negative ideal solution (A-)**	**Comprehensive score index**	**Ranking**
case 1	0.16272	0.120537	0.425539	19
case 2	0.11646	0.158215	0.576007	7
case 3	0.155408	0.095653	0.380995	22
case 4	0.127995	0.126457	0.496978	11
case 5	0.162899	0.11883	0.421788	20
case 6	0.07723	0.180007	0.699772	2
case 7	0.154805	0.126683	0.450048	15
case 8	0.058748	0.213262	0.784023	1
case 9	0.16129	0.133318	0.452527	14
case 10	0.117285	0.168246	0.589239	4
case 11	0.150254	0.113243	0.429768	18
case 12	0.125953	0.157457	0.555582	8
case 13	0.159622	0.100591	0.386572	21
case 14	0.115215	0.167286	0.59216	3
case 15	0.139912	0.146396	0.511324	9
case 16	0.152989	0.116375	0.432036	17

case 17	0.138675	0.133109	0.489761	12
case 18	0.153474	0.121656	0.442176	16
case 19	0.142442	0.145631	0.505536	10
case 20	0.115129	0.162353	0.585093	5
case 21	0.14613	0.133893	0.478149	13
case 22	0.112124	0.156698	0.582905	6
case 23	0.176261	0.108199	0.380366	23

Table 22 employs the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to evaluate and rank the performance of multiple cases. Code is listed in Appendix B.

This study adopts double benchmark extreme value analysis method to quantitatively compare and select multiple groups of schemes. By calculating the positive approximation degree between each scheme and the optimal reference system and the reverse deviation degree from the deterioration benchmark, a comprehensive adaptation index is constructed as the basis for prioritization, and the level of the index directly reflects the degree of fit between the scheme and the ideal state.

Empirical data revealed significant gradient differences in the performance of each scheme: Case 8 ranked first with 0.784 fit value, followed by Case 6 (0.699), This result is basically consistent with that of the AHP algorithm, as the 1st rank in AHP is Case 6 and the 2nd rank is Case 8.

On the contrary, for the degree of proximity to the negative ideal solution (A-), Case 23(0.3803) ranked the last(23th), Case 3(0.3809) ranked in 22nd for TOPSIS. The results have a gap compared with AHP (23rd—Case16, 22nd—Case7), which needs to be systematically improved due to the large deviation from the base value of the multidimensional index. However, both AHP and TOPSIS has the same ranking in 21st for (A-), (AHP: Case 21--0.321, TOPSIS: Case21--0.386). The two algorithms produce similar results, which can prove the feasibility of the prototype.

After multi-criterion verification, the Case-Based Reasoning decision model based on Analytic Hierarchy process (AHP) shows reliable optimisation ability of transformation scheme. This collaborative algorithm effectively avoids the subjective limitations of traditional expert evaluation and the mechanical defects of pure data model, shows significant advantages in balancing technical feasibility and practical engineering constraints, and provides a decision-making tool with both theoretical rigor and practical operability for existing building retrofit.

6.2.2 Proposed Methodology as the Early Stage Building Retrofit Strategy

To sum up, CBR approach is relatively mature in other fields and has potential to support the decision-making for building retrofit in the early stage. While it is an innovative approach, few studies have been applied till the last couple years. Several reviewed studies are worthy for learning and utilising to accomplish a better retrofit strategy.

According to the reviewed literature, most CBR models are mining the similar cases, through the widely recognised “4R” principle (Kolodner, 1992) of “Retrieve, Reuse, Revise and Retain”, or the amended “R5” theory (Finnie & Sun, 2003; Wang, et al., 2019) of identifying “Represent” at the beginning, to provide references for decision-making. This type of workflow is considered as the basic CBR models.

Based on the Plan of Work from RIBA, the most suitable stage to use this CBR model is stage 2, Concept Design. Shown in Figure 33. The goal of this stage is to determine an architectural concept that could be admitted from the clients (RIBA, 2020).

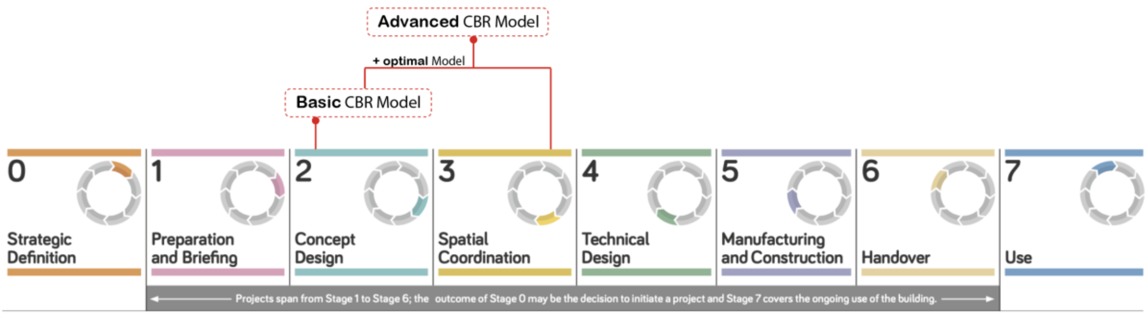


Figure 33 CBR model applications during RIBA stage

[Image by Author (Li, et al., 2024); adapted from RIBA Plan of Work 2020, Available at https://cms-group.co/the-8-riba-stages-explained/]

Clients and designers are the main participants during this phase, who would need to review the concept design and consent the design that is consistent with the budget, strategies, etc. for formulating the further detailed design program (RIBA, 2020). There is a lot of uncertainty at this stage, as amendments would be made align with the feedback from the participants. In addition, RIBA also suggests that a “pragmatic review” (RIBA, 2020) is essential to support determining the outline specification. Thus, the basic CBR models could fulfill the goals and provide a solution for these tasks.

For the basic CBR models, the whole process belongs to the concept design stage. As the outcomes are sorted based on the user’s input weight demands, which result in the combination of possible solutions that prioritise uses’ needs for building retrofit. This decision-making process involves both professionals and non-professionals, makes the basic CBR a convenient decision-making support tool.

Yet for a consensus to be reached for leading the detail design in stage 3, a further calculation of the optimal solution is mandatory. The stage 3 is about “testing and validating” (RIBA, 2020) the outcome from stage 2. Professional design teams are the key role in this stage, clients are involving here for coordination. Hence, there were also 2 research tried to combine optimisation into CBR cycle, Koo et al. (Koo, et al., 2011) and Hong et al. (Hong, et al., 2015) developed the “Advanced CBR(A-CBR) model”, which was based on the 4R theory of basic CBR model and integrate with another optimisation model together for extra evaluation process. Such proposed A-CBR model is considered to run through stage 2 and 3, as shown in Figure 33. Not only indicating the possible solutions in the early concept design stage, but also undertaking the detailed analysis and test of the potential schemes. To make sure the outcome from stage 2 could be translated into stage 4 for manufacture details. This is a different trial, yet the optimisation section is another important subject that may have better alternatives to be studied. At present, the basic CBR models would be more consistent with the common understanding of CBR principle, which is the research target for this study as well.

6.3 Limitation of the Prototype

This proposed CBR approach integrates quantitative data analytics with qualitative stakeholder engagement, to address modular retrofit decision-making. The methodology's key strengths lie in its interdisciplinary rigor and adaptability:

1. Data-Driven Modularity: By grounding the CBR framework in real-world Horizon 2020 cases, the methodology ensures solutions are empirically validated and scalable, bridging the gap between theoretical models and practical implementation.
2. Stakeholder Inclusivity: Fuzzy logic interfaces democratize decision-making, accommodating non-expert users while maintaining technical precision.

3. Dynamic Weighting: The AHP method balances competing priorities, enabling context-specific retrofit strategies.

However, the methodology faces critical limitations:

- Case Data Constraints: Reliance on incomplete or EU-centric datasets risks regional bias and underrepresentation of emerging technologies (e.g., only 12% of cases address tropical climates). Missing attributes (e.g., detailed lifecycle costs in 35% of projects) necessitate synthetic data extrapolation, introducing uncertainty.
- Expert Dependency: Weighting criteria and fuzzy logic thresholds rely on expert input, which may inadvertently embed subjective biases into the CBR model.
- Scalability Challenges: While the prototype demonstrates feasibility, scaling the framework globally requires partnerships to standardize data reporting and expand case libraries.

Despite these limitations, the methodology provides a foundational blueprint for advancing modular retrofits, emphasizing iterative improvement over immediate perfection.

Furthermore, this thesis prioritizes the development of a functional CBR prototype, necessitating pragmatic compromises in three key areas:

1. Case Database Scope: The prototype's reliance on Horizon 2020 projects introduces geographic and technological biases. Yet, not all of those innovation project has a complete and detailed description, which cause a challenge in summarising and defining the attributes. Additionally, emerging technologies and unconventional building types (e.g., informal settlements) remain underrepresented, narrowing the model's versatility.
2. Attribute Completeness: While the core attributes (e.g., U-value, cost) were standardized, critical metrics like lifecycle carbon emissions and social equity impacts were inconsistently reported in case studies, forcing reliance on proxies or synthetic data. This risks oversimplifying retrofit outcomes in sustainability assessments.
3. Interface Functionality: The prototype's interface, though user-friendly, sacrifices granularity for accessibility. For example, fuzzy inputs ("Low Cost") mask nuanced cost variations, potentially misaligning user intent with system recommendations. Furthermore, real-time collaboration features (e.g., multi-stakeholder editing) were deferred to prioritize core functionality.

These limitations underscore the prototype's role as a foundational iteration rather than a finalized solution. However, they also delineate clear pathways for refinement, positioning the framework for incremental enhancement as richer datasets and user feedback become available.

6.4 Summary

In general, CBR model based on AHP algorithm has its clear advantages, which is beneficial for early stage design decision making. The hierarchy calculation of AHP (Figure 16 Construction of hierarchy for AHP) can clearly decompose complex problems, which offers a more straight-forward outcome. Yet, the limitation of this model is also clear, as AHP is sensitive to extreme scores, which makes this model relies on the subjective judgements. This could tend to amplify errors. As this research is presenting the CBR model as a prototype, there will be many directions can be further developed in the future work, this part will be discussed in the next Chapter 7.

7 Conclusion

7.1 Conclusions

This thesis systematically addresses the challenges of scaling modular building retrofits through a novel Case-Based Reasoning (CBR) framework, bridging theoretical innovation with practical implementation. Below is a synthesis of each chapter's contributions and findings:

Chapter 1: Introduction

The main aim of this chapter is to identify the urgency of retrofitting ageing building stock to meet the EU's decarbonisation targets by understanding the existing energy retrofit context. Based on the analysis of relevant studies, the gaps in existing retrofit decision-making tools are identified and the CBR method is introduced as a solution.

In this chapter, the research aim is raised, which is to provide a scalable solution for energy efficiency modular retrofit, but requires a systematic, data-driven approach to overcome fragmentation. To solve the problems, the structure of the thesis is conducted based on the 3 research questions from section 1.3.1.

Chapter 2: Methodology

The philosophy of Methodology is referenced based on the literature review of DRM (Design Research Methodology) framework. It is consisting of 4 stages: RC—Research Clarification (review-based, filter preliminary criteria), DS I—Descriptive Study I (considering as the network of influencing factors/ involve the reference model to setup the database), PS—Prescriptive Study (propose the impact model), and DS II—Descriptive Study II (evaluation). This methodology emphasises the advantages of a hybrid (case & algorithm) approach in balancing theory/practice and addressing subjectivity, such as expert judgements. The workflow of DRM established the structure of researching the thesis step by step, which developed the logic and connect for the following each chapter.

Chapter 3: Literature Review

As the stage 1: RC—Research Clarification (review-based, filter preliminary criteria). This chapter of Literature review critiques existing research hierarchically from targeted building, modular design, existing building retrofit, energy efficiency retrofit and multi-criteria decision making approach. The review highlighted the lack of scalable, user-centric frameworks. Thus, modular retrofits remain understudied in the context of dynamic, multi-criteria decision support.

In this case, the Case-Based Reasoning approach with AHP algorithm is conducted from the research and analysis, which leads to design the CBR model in next chapter.

Chapter 4: Case-Based Reasoning Approach

In this chapter, the content is considered as the stage 2 from Methodology: DS I—Descriptive Study I. The main goal is to understand the CBR workflow(retrieve-reuse-revise-retain) and to investigate appropriate algorithms for CBR model. Understand the parameters required for dynamic weighting mechanisms to determine ranges and define multidimensional attributes for transformation policy matching.

This understanding leads to the logic of how to review the case studies to build up the database for CBR model, which come up with the attributes need to be analysed and summarised for the next chapter.

Chapter 5: CBR Decision-Making Support

This chapter is stage 3: PS—Prescriptive Study (propose the impact model). By reviewing the selected case studies from H2020 projects, a functional prototype is developed within intuitive interface, addressing limitations in data completeness through synthetic case generation. This user-centric design democratizes access to complex retrofit strategies, even with imperfect datasets. A demonstration of prototype is also presented.

However, this prototype has its advantages and limitations, which is further discussed in Chapter 6.

Chapter 6: Discussion

This Chapter is the final stage 4: DS II—Descriptive Study II (evaluation). The accuracy of CBR-AHP is tested with a cross-validation by TOPSIS, which is a borrowed strategy from the research done by Dagdeviren, et al. (Dagdeviren, et al., 2009). However, limitations of the CBR framework emerged, including dependency on case library completeness, sensitivity to subjective attribute definitions, and challenges in handling dynamic criteria.

While CBR-AHP demonstrates adaptability for standardised retrofit schemes, its effectiveness is reduced where data is scarce or rapidly changed. In this case, the database plays an essential role in affecting the outcome. Dynamic case adaptation rules and collaborative databases could address system bias and scalability barriers.

7.2 Contributions

Modular retrofit strategy would be built up on the existing research and practical projects of sustainable retrofit. Appraising the existing state and challenge of the modular approach. The user interface parameter-selecting tool based on the database of available renewable technologies introduces the potential optimized integration design for the individual target.

This thesis makes three pivotal contributions:

- Theoretical: A structured CBR framework that integrates modular retrofit intelligence into a replicable decision-making process, addressing the gap between fragmented case studies and systemic solutions.
- Practical: A prototype tool that empowers non-experts to navigate retrofit planning via fuzzy logic and visual analytics, demonstrating feasibility in real-world scenarios.
- Scalability: Alignment with EU Renovation Wave objectives, providing a blueprint for scalable, data-driven decarbonization strategies.

7.3 Future Work

In summary, there are several important directions that worth to be further investigated to advance the CBR retrofit framework:

- High-Quality, Collaborative Case Databases:

The effectiveness of the CBR model depends on a comprehensive and reliable case database. While architectural datasets (e.g., ASHRAE's Building Energy Database) provide foundational references, open-access platforms integrating multidisciplinary retrofit data—encompassing technical specifications, cost metrics, and post-occupancy evaluations—are essential to improve model accuracy. Collaborative initiatives between research institutions and industry stakeholders could standardise data formats, attribute definitions and criteria, etc., which enables the aggregation of massive datasets for robust machine learning applications.

- Integration of Optimisation Algorithms:

Current CBR model often lacks the optimisation mechanism, which limits the adaptability to complex retrofit scenarios. For instance, the hybrid frameworks such as the A-CBR model (Adaptive Case-Based Reasoning) (Koo, et al., 2011) (Hong, et al., 2015) , could embed metaheuristic algorithms (e.g., genetic algorithms, particle swarm optimisation) to refine solution rankings dynamically. Combining CBR with other multi-objective optimisation approaches could balance competing priorities like energy efficiency, heritage preservation, and budget constraints in real time.

- Expert-Driven Attribute Standardization:

The credibility of case attributes (e.g., “energy performance”, the weights ratio of attributes, etc.) requires validation by domain authorities. Partnerships with institutions like the Royal Institute of British Architects (RIBA) or the International Energy Agency (IEA) could establish globally recognized benchmarking criteria (RIBA, 2020)(IEA, 2021). A panel of experts can review the case base to eliminate outliers and ensure that attributes reflect real-world retrofit priorities rather than theoretical assumptions.

- Computer-Aided Interface Refinement:

Existing CBR interfaces often have limited scalability or user accessibility. Re-engineering these tools with advanced computing architectures—such as cloud-based platforms with API integration or interactive 3D visualisation modules—could broaden their applicability.

Synergistic advancements in these areas—data democratisation, algorithmic hybridity, expert validation, and computational usability—could transform CBR from a niche decision-support tool into a mainstream platform for sustainable building retrofits.

Appendix

Appendix A Analysis Information of the Case Study

This name of cases is shown in Table 9.

	On-site Construction	Total Period	Cost
Case1	0.5(2weeks)	57	€ 4 597 455
Case2	N/A	54	€ 10 259 963
Case3	2(prototype)	48	€ 4 994 795
Case4	N/A	48	€ 4 914 210
Case5	N/A	54	€ 5 849 107
Case6	N/A	54	€ 9 050 448
Case7	units on the external wall - 1-2days BEMs unit - 1 m2 of E2VENT ventilated facade - 80 minutes/1 worker	42	€ 3 402 789
Case8	N/A	58	€ 6 926 301
Case9	less than 4(in a semester)	63	€ 5 981 316
Case10	2	58	€ 6 638 688
Case11	N/A	54	€ 7 934 578
Case12	N/A	42	€ 8 606 893
Case13	N/A	48	€ 6 041 474
Case14	N/A	48	€ 10 841 678
Case15	3（based on installed facade)	60	€ 9 934 577
Case16	N/A	42	€ 5 038 667
Case17	N/A	54	€ 5 634 811
Case18	near 3(spring-summer)	63	€ 6 860 026
Case19	N/A	65	€ 4 975 339
Case20	3(most completed in summer, but one delayed by Covid-19)	48	€ 8 323 209
Case21	N/A	36	€ 6 847 730
Case22	N/A	52	€ 8 708 052
Case23	N/A	48	€ 9 969 768

	Aim Building and Areas	Real case study
Case1	residential buildings	the work on the Norwegian demo-case, in the Netherlands, Spain
Case2	European Public Buildings	three real demo-sites (an office building in Bilbao, Spain; a cafeteria building in Ankara, Turkey; technological museum in Malmö, Sweden
Case3	residential buildings (existing stock)	demonstrations in Dutch, French and Polish.
Case4	timber prefabricated modules	two real buildings in two different climatic zones (South and North Europe).
Case5	An envelope system for buildings refurbishment	a single floor with a total of 545m² area in Burgos University, Spain.
Case6	residential buildings	N/A（This is just a Tool Kit）
Case7	residential and commercial buildings	the two buildings in Gdansk, Poland and Burgos, Spain
Case8	residential buildings	N/A
Case9	buildings' Envelopes	N/A
Case10	existing residential building stock, new residential and commercial buildings. Central and Southern Europe	European multistorey residential buildings dating from the second half of the 20th century
Case11	residential buildings	infrastructure at the Valencia, Chorzow pilot sites
Case12	existing residential buildings	Thirteen domestic buildings of different ages in seven different countries across Europe
Case13	Buildings dated between 1950 and 1975(bad energy efficient performance)	the two different types of demo buildings in Romania and Ireland
Case14	residential and office buildings	two demo buildings in Madrid and in Ludwigsburg
Case15	Europe residential buildings	residential building in Mérida, Spain.
Case16	buildings' Envelopes	N/A
Case17	residential buildings	N/A
Case18	both residential and non-residential buildings.	Four different multi-building Pilots in Germany, Spain, Greece and the U.K.
Case19	residential buildings	Student house, B FEPA building, University of Athens
Case20	European ageing and inefficient residential building	four apartment block buildings (Spain, Switzerland, UK and Denmark)
Case21	residential buildings	249 houses were renovated in the Netherlands, the demonstrator in Spain and Poland.
Case22	residential buildings	the digitalization of the Building Demos in DURANGO (Spain) and in VORU (Estonia)
Case23	residential buildings	three building pilots (Spain, Germany and Sweden)

	Pre-fab/On-site	Replaceable	Installation place
Case1	technology concepts and business models	N/A	N/A
Case2	On-site Retrofitting	N/A	windows, Façade, insulation panels
Case3	On-site Retrofitting	N/A	Façade, wall system
Case4	On-site Retrofitting	N/A	facades
Case5	On-site Retrofitting	easy assembly and disassembly	windows, Façade, insulation panels
Case6	On-site Retrofitting	N/A	facades
Case7	On-site Retrofitting	N/A	N/A
Case8	On-site Retrofitting	N/A	envelope, windows
Case9	On-site Retrofitting	easy assembly	envelope (facades and roofs)
Case10	On-site Retrofitting(toolkit)	N/A	envelope, windows
Case11	On-site Retrofitting	easy assembly	N/A
Case12	On-site Retrofitting (Computer model)	N/A	envelope (facades and windows)
Case13	pre-fabricated	easy assembly	exterior pre-fabricated concrete panels
Case14	pre-fabricated	easy assembly	envelope (a new high performance prefabricated timber envelope around the building, integrated with multi-systems)
Case15	pre-fabricated: Standardised dimensions for panels and modules	Low maintenance, easy assembly and disassembly	Façade system
Case16	On-site Retrofitting	easy assembly	facades
Case17	pre-fabricated(customized)	easy assembly	envelope(roof)
Case18	On-site Retrofitting	N/A	Façade
Case19	pre-fabricated	easy assembly	envelope, shell
Case20	On-site Retrofitting: customizable model with a visual system	N/A	windows, Façade, insulation panels
Case21	pre-fabricated: Energy Module	Low maintenance, easy assembly	N/A
Case22	On-site Retrofitting	easy assembly	N/A
Case23	half-pre-fabricated	easy assembly	facades, windows

	Transformation method	Technology
Case1	N/A	Solar collector; Photovoltaic
Case2	Lighting System, Thermal System	Lighting, Solar shading, Ventilation, Solar collector
Case3	N/A	Solar shading, Ventilation, Solar collector
Case4	N/A	Facade materials
Case5	Energy Management System	Ventilation, Solar shading, Solar collector, Photovoltaic
Case6	thermal system, air system, power system, storage	Photovoltaic， Geothermal energy
Case7	Air System, Thermal System, Management System	Ventilation, Solar collector
Case8	Thermal System, air system.	Photovoltaic
Case9	Storage, Management System	Solar collector; Photovoltaic
Case10	Power system, Energy System, Air System, Thermal System	Ventilation; Solar shading; Solar collector, Photovoltaic
Case11	energy management system	Photovoltaic; Solar collector
Case12	lighting System, Thermal System, energy system, air system.	Lighting, Solar shading, Ventilation, Solar collector, Photovoltaic, Geothermal energy, Computer models
Case13	N/A	3D Printed Facade materials for Insulation
Case14	N/A	HVAC， lighting and shading systems, Solar collector
Case15	N/A	Ventilation, Solar shading, PVT (Solar collector, Photovoltaic)
Case16	N/A	Solar shading
Case17	N/A	Solar collector; Photovoltaic
Case18	Power system, Energy System, Storage	Solar collector, Photovoltaic (renewable energy generation and storage)
Case19	N/A	Photovoltaic
Case20	Air System, Energy Management System	Ventilation, Photovoltaic, Solar shading (smart windows)
Case21	Power system	a standardised pre-fabricated energy module equipped with communication technology
Case22	energy system	Solar collector, Photovoltaic; Geothermal heat
Case23	power System, Thermal System, air system	Solar collector; Photovoltaic

	Energy Performance		
	Material/Construction Structure	**Energy Saving**	**Payback time**
Case1	prefabricated timber facades	60%-70%;	15% reduction of life cycle costs over 30 years
Case2	insulation layer façade, VIP,	50%	7 years
Case3	lightweight concrete, adaptable polymer materials, total heat exchanger	65%	14 years
Case4	timber facades	50%	N/A
Case5	fibre reinforced concrete	76.40%	N/A
Case6	PV inverter, metal substructure façade, ICT infrastructure	63%-71%;	N/A
Case7	phase change materials	70% Energy savings of more than 40%, Typical performance target of less than 25 kWh/m 2 year (excluding appliances)	N/A
Case8	N/A	70%	N/A
Case 9	new solar heat collectors in facade, heat harvesting ventilated glass	75%	N/A
Case10	DC heat pump, thermal storage, smart fan-coil, MIMO converter, façade panels, PV tiles, IoT devices and components for windows retrofit	80%-90%;	⩽15 years
Case11	integration of RES (PV and Solar thermal)	20%-30%;	< 10 years
Case12	PCM, VIPs, PV façade, LED lamps and light pipes	⩾ 80%;	2-5 years
Case13	polyurethane pane, lightweight pre-cast concrete, Phase Change Material	the recladding panels:8% per year; Hypucem panels: the U-Value of the external walls would reduce from 1.54 to 0.19 W/m2K; Severin demonstrator: energy saving 22% per year; potential time savings: 30%	N/A

Case14	façade-integrated micro heat pump, wooden-frame envelope modules, mechanical ventilation unit	an overall Primary Energy consumption of the building lower than 50 kWh/m²/year.	N/A
Case15	thermoplastic polymers composite materials	up to 60%	less than 7 years
Case16	clay aerogel, PCMs, fly ash, FRP, organic combustible plasticizer	N/A	N/A
Case17	N/A	N/A	⩽8years
Case18	PnH double façade	N/A	<10years
Case19	timber-based components, aluminium windows, PV and solar panels	88%	N/A
Case20	VIP, CPV, PCMs, The Cooling evaporative Kit	71%-90%	less than 15 years
Case21	N/A	60%	N/A
Case22	Modular “plug and play” facades	⩾60%;	⩽15 years
Case23	semi-industrial coatings	N/A	7 years

Appendix B Coding for CBR Programming in AHP & TOPSIS

1. **Calculation Under AHP：**

```
import numpy as np
import pandas as pd

def convert_to_number(x):
    """Convert qualitative grades to numeric scale"""
    mapping = {
        'very low': 1,
        'low': 2,
        'medium': 3,
        'high': 4,
        'very high': 5,
        'Very Low': 1,
        'Low': 2,
        'Medium': 3,
        'High': 4,
        'Very High': 5
    }
    if isinstance(x, str):
        return mapping.get(x.strip(), np.nan)
    return x

def convert_grades(df):
    """Convert all dataframe values to numbers"""
    return df.applymap(convert_to_number)

def calculate_entropyweight(df):
    """Entropy weight method"""
    df = df.astype(float)
    # Normalize by column
    P = df / df.sum()
    # Entropy
    k = 1.0 / np.log(len(df))
    E = -k * (P * np.log(P + 1e-12)).sum()
    d = 1 - E
```

```
    w = d / d.sum()
    return w.values

def topsis(df, weights, impacts=None):
    """
    TOPSIS method with impacts support
    df: decision matrix (rows: alternatives, cols: criteria)
    weights: list or array of weights
    impacts: list of '+' (benefit) or '-' (cost) for each criterion
    """
    df = df.astype(float)
    weights = np.array(weights)

    # Step 1: Normalize
    norm = df / np.sqrt((df ** 2).sum())

    # Step 2: Weighted normalized decision matrix
    weighted = norm * weights

    # Step 3: Handle impacts
    if impacts is not None:
        for i, impact in enumerate(impacts):
            if impact == '-':
                # For cost criteria, reverse column values
                weighted.iloc[:, i] = -weighted.iloc[:, i]

    # Step 4: Ideal and anti-ideal
    ideal_best = weighted.max()
    ideal_worst = weighted.min()

    # Step 5: Distances
    dist_best = np.sqrt(((weighted - ideal_best) ** 2).sum(axis=1))
    dist_worst = np.sqrt(((weighted - ideal_worst) ** 2).sum(axis=1))

    # Step 6: Closeness coefficient
    score = dist_worst / (dist_best + dist_worst)

    # Step 7: Result dataframe
```

```
    result = df.copy()
    result['Score'] = score
    result = result.sort_values(by='Score', ascending=False)

    return result, score
```

2. **Calculation Combining TOPSIS:**

```
import pandas as pd
import numpy as np
import Topsis
import AHP

df = pd.read_excel('re_data.xlsx', index_col=0)
df_numeric = Topsis.convert_grades(df).astype("float32")

df_a = pd.read_excel('re_matrix.xlsx', index_col=0)
weight_a = AHP.ahp(df_a)
weight_a = weight_a / np.sum(weight_a)

weight_b = Topsis.calculate_entropyweight(df_numeric)
weight_b = weight_b / np.sum(weight_b)

impacts = ['-', '-', '-', '+', '+']

out = Topsis.topsis(df_numeric, weight_a)
out2 = Topsis.topsis(df_numeric, weight_b)

out[0].to_excel("AHP_new.xlsx")
out2[0].to_excel("Topsis_new.xlsx")
print(out[0].iloc[:, -1])
print(out2[0].iloc[:, -1])

print(weight_a)
print(weight_b)
```

Appendix C Coding for Interface

First Step: Create the main User Interface(UI) window

1. Ui_MainWindow()

```python
1 usage
class parentWindow(QMainWindow):
    def __init__(self):
        QMainWindow.__init__(self)
        # 创建窗口对象
        self.main_ui = Ui_MainWindow()
        # self.main_ui.__init__()
        # 开放用户界面所有交互的权限
        self.main_ui.setupUi(self)
        # 翻译部分按键中的文字
        self.main_ui.retranslateUi(self)
```

```python
class Ui_MainWindow(QMainWindow):
    def __init__(self):
        super().__init__()
        self.setupUi(self)
        self.retranslateUi(self)
```

2. main_ui.setupUi()

```python
    def setupUi(self, MainWindow):
        MainWindow.setObjectName("MainWindow")
        MainWindow.resize(1401, 973)
        MainWindow.setAcceptDrops(False)
        MainWindow.setStyleSheet("background:rgb(255, 255, 255)")
        self.centralwidget = QtWidgets.QWidget(MainWindow)
        self.centralwidget.setObjectName("centralwidget")
        self.verticalLayout = QtWidgets.QVBoxLayout(self.centralwidget)
        self.verticalLayout.setContentsMargins(0, 0, 0, 0)
        self.verticalLayout.setSpacing(0)
        self.verticalLayout.setObjectName("verticalLayout")
        self.widget_top = QtWidgets.QWidget(self.centralwidget)
        self.widget_top.setStyleSheet("background:rgb(127, 127, 127)\n"
"")
        self.widget_top.setObjectName("widget_top")
        self.horizontalLayout_3 = QtWidgets.QHBoxLayout(self.widget_top)
        self.horizontalLayout_3.setObjectName("horizontalLayout_3")
        spacerItem = QtWidgets.QSpacerItem(40, 20, QtWidgets.QSizePolicy.Expanding, QtWidgets.QSizePolicy.Minimum)
        self.horizontalLayout_3.addItem(spacerItem)
        self.label_13 = QtWidgets.QLabel(self.widget_top)
        self.label_13.setText("")
        self.label_13.setPixmap(QtGui.QPixmap("icon/建筑.svg"))
        self.label_13.setObjectName("label_13")
        self.horizontalLayout_3.addWidget(self.label_13)
        spacerItem1 = QtWidgets.QSpacerItem(293, 20, QtWidgets.QSizePolicy.Expanding, QtWidgets.QSizePolicy.Minimum
        self.horizontalLayout_3.addItem(spacerItem1)
        self.label = QtWidgets.QLabel(self.widget_top)
        self.label.setStyleSheet("color:rgb(255, 255, 255);\n"
"ont: 18pt \"Arial\";")
```

3. add_function()

```python
def add_function(self):
    self.case = {'name':'test', 'U value': 1, 'comlexity':'very low', 'insulation capacity':'very low', 'possibil
    self.line = []
    self.importance = {'comlexity': 2, 'insulation capacity': 2, 'possibility for condenstation': 2, 'constructi
    self.icnt = 0

    # sys.stdout = EmittingStr(textWritten=self.set_logging_func) # 输出重定向
    # sys.stderr = EmittingStr(textWritten=self.set_logging_func)

    self.buttonGroup.buttonClicked.connect(self.choose_importance)
    self.buttonGroup_2.buttonClicked.connect(self.choose_importance)
    self.buttonGroup_3.buttonClicked.connect(self.choose_importance)
    self.sublime_pushButton_0.clicked.connect(self.submit_importance)

    self.comboBox_0.currentIndexChanged[str].connect(self.add_case_value)
    self.comboBox_1.currentIndexChanged[str].connect(self.add_case_value)
    self.comboBox_2.currentIndexChanged[str].connect(self.add_case_value)
    self.comboBox_3.currentIndexChanged[str].connect(self.add_case_value)
    self.comboBox_4.currentIndexChanged[str].connect(self.add_case_value)
    self.comboBox_5.currentIndexChanged[str].connect(self.add_case_value)

    self.pushButton_0.clicked.connect(lambda: self.execute())
    self.pushButton_1.clicked.connect(lambda: self.add_case())

    self.show_pushButton.clicked.connect(self.show_table)
```

Reading data and performing pre-processing is equivalent to the data import function triggered by clicking a button:

```python
df = pd.read_excel('re_data.xlsx', index_col=0)
df_numeric = Topsis.convert_grades(df).astype("float32")
```

4. choose_importance()

```python
def choose_importance(self):
    sender = self.sender()
    if sender == self.buttonGroup:
        print(self.buttonGroup.checkedId())
        if self.buttonGroup.checkedId() == -5:
            self.importance['comlexity'] = 0
        elif self.buttonGroup.checkedId() == -3:
            self.importance['insulation capacity'] = 0
        elif self.buttonGroup.checkedId() == -4:
            self.importance['possibility for condenstation'] = 0
        elif self.buttonGroup.checkedId() == -2:
            self.importance['construction time'] = 0
        elif self.buttonGroup.checkedId() == -6:
            self.importance['pattern'] = 0
        print('group 0')
    elif sender == self.buttonGroup_2:
        print(self.buttonGroup_2.checkedId())
        if self.buttonGroup.checkedId() == -6:
            self.importance['comlexity'] = 1
        elif self.buttonGroup.checkedId() == -3:
            self.importance['insulation capacity'] = 1
        elif self.buttonGroup.checkedId() == -5:
            self.importance['possibility for condenstation'] = 1
        elif self.buttonGroup.checkedId() == -2:
            self.importance['construction time'] = 1
```

After choosing the importance, this function will print the preferred content on the console

```
df_a = pd.read_excel('re_matrix.xlsx', index_col=0)
weight_a = AHP.ahp(df_a)
weight_a = weight_a / np.sum(weight_a)
```

Read the AHP judgment matrix, calculate the weights, and represent the user’s preference choices

5. show_table()

```
def show_table(self):
###===========读取表格，转换表格，==========================================
    path_openfile_name = 'Case-to-Case_v2_Result.xlsx'
    if len(path_openfile_name) > 0:
        input_table = pd.read_excel(path_openfile_name)
    #print(input_table)
        input_table_rows = input_table.shape[0]
        input_table_colunms = input_table.shape[1]

        input_table_header = input_table.columns.values.tolist()
        input_table_header[0] = 'case name'
        print(input_table_header)

    ###===========读取表格，转换表格，==========================================
    ###======================给tablewidget设置行列表头==========================

        self.tableWidget.setColumnCount(input_table_colunms)
        self.tableWidget.setRowCount(input_table_rows)
        self.tableWidget.setHorizontalHeaderLabels(input_table_header)
        self.tableWidget.setSelectionMode(QAbstractItemView.SingleSelection)  # 设置只能选中一行
        self.tableWidget.horizontalHeader().setSectionResizeMode(QHeaderView.Stretch)#所有列自动拉伸，充满界面
        self.tableWidget.setEditTriggers(QAbstractItemView.NoEditTriggers)  # can't change

        self.tableWidget.resizeColumnsToContents()#设置列宽高按照内容自适应
        self.tableWidget.resizeRowsToContents()#设置行宽和高按照内容自适应
```

```
out = Topsis.topsis(df_numeric, weight_a)
out2 = Topsis.topsis(df_numeric, weight_b)
out[0].to_excel("AHP_new.xlsx")
out2[0].to_excel("Topsis_new.xlsx")
print(out[0].iloc[:, -1])
print(out2[0].iloc[:, -1])
```

To truly start the computing process is equivalent to a new thread executing a task. Output the result to an Excel file and display it in the console.

Bibliography

[1] Hongwei, Y., Jones, P. & Conghong, L., 2017. A Review on Case Studies of Domestic Retrofit Research in the UK. *The architect*, 2, pp. 6-25.

[2] Jones, P., Lannon, S. & Patterson , J., 2013. Retrofitting existing housing: how far, how much?. *Journal of Building Research & Information*, 41(5), pp. 532-550.

[3] Capeluto, I. & Ochoa, C., 2014. Simulation-based method to determine climatic energy strategies of an adaptable building retrofit façade system. *Energy*, Volume 76, pp. 375-384.

[4] Crilly, M., Lemon, M., Wright, A. J., Wright, A., Cook, M.B. & Shaw, D., 2012. Retrofitting Homes for Energy Efficiency: An Integrated Approach to Innovation in the Low-Carbon Overhaul of UK Social Housing. *Energy & Environment*, 23(6/7), pp. 1027-1055.

[5] Dave, M. & Prasad, D. K., 2010. Residential Retrofitting: Current Practice and Emerging Directions - Summary of a BEIIC Report. *Environment Design Guide*, GEN86, pp. 1-10.

[6] Ruparathna, R., Hewage, K. & Sadiq, R., 2016. Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings. *Renewable and Sustainable Energy Reviews*, Volume 53, pp. 1032-1045.

[7] Jurasz, J. & Campanabc, P. E., 2019. The potential of photovoltaic systems to reduce energy costs for office buildings in time-dependent and peak-load-dependent tariffs. *Sustainable Cities and Society,* Volume 44, pp. 871-879.

[8] Tran, T. V., Islam, M. R., Sutanto, D. & Muttaqi, K., 2019. Mitigation of Solar PV Intermittency Using Ramp-Rate Control of Energy Buffer Unit. *IEEE Trans Energy Convers,* Volume 34, pp. 435-445.

[9] Mosaffa A.H., & Farshi, L. G., 2018. Thermodynamic and economic assessments of a novel. *Renewable Energy,* Volume 120, pp. 134-150.

[10] Shan, K., Wang, J., Hu, M. & Gao, D., 2019. A model-based control strategy to recover cooling energy from thermal mass in commercial buildings. *Energy,* Volume 172, pp. 958-967.

[11] English Heritage, 2010. *PREFABS - Factory homes for post-War England.* [Online] Available at: www.english-heritage.org.uk.[Accessed 2010].

[12] MBE Consultants, 2010. *MBE Consultants in Technical Refurbishment LLP.* [Online] Available at: http://mbeconsultants.com/Cornish.html[Accessed 2010].

[13] BISF, 2010. *BISF House.* [Online] Available at: foursteelwalls.co.uk.[Accessed 2010].

[14] Madge, J., 2006. *Tomorrow's Houses.* London: Read Books.

[15] Matthew, S., 2003. *The century makers: 1945.* London: The Telegraph.

[16] Blanchet, E. & Sonia, Z., 2018. *PREFABS - A social and architectural history.* Liverpool: Liverpool University Press.

[17] Miller , T. D. & Elgård, P., 1998. Defining Modules, Modularity and Modularization Evolution of the Concept in a Historical Perspective. *Proceedings of the 13th IPS Research Seminar,* Fuglsoe, pp.19.

[18] Ma, Z., Cooper, P., Daly, D. & Ledo, L., 2012. Existing building retrofits: Methodology and state-of-the-art. *Energy and builings*, Volume 55, pp. 889-902.

[19] Fulton , M. & Grady , H., 2012. *United States Building Energy Efficiency Retrofits Maket Sizing and Financing Models.* Frankfurt : Deutsche Bank AG.

[20] Hamza, H., Belaïd, Y. & Belaïd, A., 2007. *Case-based reasoning for invoice analysis and recognition..* Berlin, Heidelberg, Springer, pp. 404-418.

[21] Gero, J. S., D'Cruz, N. A. & Radford, A. D., 1983. Energy in context: A multicriteria model for building design. *Building and Environment*, 18(3), pp. 99-107.

[22] Menassa, C. C., 2011. Evaluating sustainable retrofits in existing buildings under uncertainty. *Energy and Buildings*, 43(12), pp. 3576-3583.

[23] Flourentzou, F. & Roule, C. A., 2002. Elaboration of retrofit scenarios. *Energy and Buildings*, 34(2), pp. 185-192.

[24] Seyis, S. & Ergen, E., 2017. A decision making support tool for selecting green building certification credits based on project delivery attributes. *Building and Environment,* Volume 126, pp. 107-118.

[25] Sangiorgio, V., Vargas, L. G., Fatiguso, F. & Fiorito, F., 2022. AR-AHP to Support the Building Retrofitting: Selection of the Best Precast Concrete Panel Cladding. In: *New Approaches for Multi-Criteria Analysis in Building Constructions.* Cham, Switzerland: Springer, pp. 83–101.

[26] Haroun, H.-A. A. F., Bakr, A. F. & Hasan, A. E.-S., 2019. Multi-criteria decision making for adaptive reuse of heritage buildings: Aziza Fahmy Palace, Alexandria, Egypt. *Alexandria Engineering Journal,* Volume 58, pp. 467-478.

[27] Ahmad, T., Aibinu, A. & Thaheem, M. J., 2017. BIM-based iterative tool for sustainable building design: A conceptual framework. *Procedia Engineering*, Volume 180, pp. 782-792.

[28] Kolodner, J., 1993. *Case based reasoning.* San Mateo: Morgan Kaufmann.

[29] Blessing, L., Chakrabarti, A. & Wallace, K., 2009. *DRM: A Design Research Methodology.* London: Springer.

[30] Blanchet, E. & Zhurablyova, S., 2018. *Prefab Housing and the Post-War British Home.* Swindon:Historic England.

[31] Great Britain, 2007. *Housing (Temporary Accommodation) Act 1944,* Cambridge.: Proquest LLC.

[32] Ulrich, K., Eppinger, S. & Yang, C. Y., 2020. *Product Design and Development.* New York.:McGraw-Hill Education.

[33] Hövels, J., 2008. *Openable Modular Facade Concept.* [Online] Available at: https://repository.tudelft.nl/record/uuid:e08cc238-f4b6-4c4d-bbd1-bc7d0e821025[Accessed 2020].

[34] Alajmi, A., 2021. High- vs. Low-Cost ECMs in Commercial Buildings.. *Energy and Buildings*, Volume 253, pp. 111532.

[35] Atmaja, T. D., 2013. Façade and rooftop PV installation strategy for building integrated photo voltaic application. *Energy Procedia,* Volume 32, pp. 105-114.

[36] Hernández-López, I., Xamán, J., Zavala-Guillén, I. & Pérez, H. I., 2020. Thermal performance of a solar façade system for building ventilation in the southeast of Mexico. *Renewable Energy,* 1, Volume 145, pp. 294-307.

[37] Ahmed, M., Abdel-Rahman, A. K., Ahmed, H. A. H. & Suzuki, M., 2016. Double Skin Façade: The state of art on Building Energy efficiency. *Journal of Clean Energy Technologies,* 4(1), pp. 84-89.

[38] Aghamolaei, R., Shams, M. H., Tahsildoost, M. & Donnell, J. O., 2018. Review of district-scale energy performance analysis: Outlooks towards holistic urban frameworks. *Sustainable Cities and Society,* Volume 41, pp. 252-264.

[39] Costa-Carrapiçoa, I., Raslanb, R. & González, J. N., 2020. A systematic review of genetic algorithm-based multi-objective optimisation for building retrofitting strategies towards energy efficiency. *Energy & Buildings*, Volume 210, pp. 109690.

[40] Zhang, M., 2014. An Improved Apriori Algorithm for Mining Association Rules. *International Journal of Information Technology and Computer Science,* 6(7), pp. 15-23.

[41] Climate Change Act 2008, 2008. *Climate Change Act 2008 part 1. The target for 2050.* [Online] Available at: https://www.legislation.gov.uk/ukpga/2008/27/part/1[Accessed 2020].

[42] Ministry of Housing, Communities & Local Government, 2016. *English Housing Survey 2016 to 2017: headline report.* [Online] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/705821/2016-17_EHS_Headline_Report.pdf[Accessed 2018].

[43] U.S. Environmental Protection Agency, 2023. *ENERGY STAR Rebates and Incentives*. [Online] Available at: https://www.energystar.gov/rebate-finder.[Accessed 2023]

[44] Queensland Treasury, 2009. Q*ueensland Budget: Building a Greener Future. Queensland Government.* [Online] Available at: https://budget.qld.gov.au.[Accessed 2023]

[45] Nuala, B. & Iona, S., 2025. *The UK's Plans and Progress to Reach Net Zero by 2050.* [Online] Available at: https://researchbriefings.files.parliament.uk/documents/CBP-9888/CBP-9888.pdf [Accessed 2025].

[46] European Commission, 2025. *Energy Performance of Buildings Directive.* [Online]
Available at: https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/energy-performance-buildings-directive_en#:~:text=85%25%20of%20EU%20buildings%20were,remains%20very%20low%20at%201%25.[Accessed 2025].

[47] Perina, M., Quenard, D. & Wakili, K. G., 2017. Building retrofit: Energy conservation, comfort and sustainability. *Energy and Buildings,* Volume 152, pp. 40.

[48] Liu, G., Li, X., Tan, Y. & Zhang, G., 2020. Building green retrofit in China: Policies, barriers and recommendations. *Energy Policy,* Volume 139, pp. 111356.

[49] Park, S., Park, S., Jang, H., Ahn, Y. & Kwon, N., 2025. Computing green remodeling construction cost for public buildings based on genetic algorithm and case-based reasoning. *Developments in the Built Environment,* Volume 22, pp. 100655.

[50] Liu, T., Ma, G., Wang, D. & Pan, X., 2024. Intelligent green retrofitting of existing buildings based on case-based reasoning and random forest. *Automation in Construction,* Volume 162, pp. 105377.

[51] HM Government, 2021. *Net Zero Strategy: Build Back Greener.* [Online] Available at: https://www.nea.org.uk/who-we-are/retrofit-technical-research/.[Accessed 2022].

[52] NHBC Foundation, 2022. *The connected home.* [Online] Available at: https://www.nhbc.co.uk/kontentdocuments/9c972f44-efc0-46bc-b7bb-8b76b2e13175/the-connected-home.pdf.[Accessed 2022].

[53] Climate Change Committee, 2019. *UK housing: Fit for the future?.* [Online] Available at: https://www.theccc.org.uk/publication/uk-housing-fit-for-the-future/.[Accessed 2019].

[54] National Energy Action, 2022. *Retrofit and Technical Research.* [Online] Available at: https://www.nea.org.uk/who-we-are/retrofit-technical-research/.[Accessed 2022].

[55] Penrose, S., 2010. *Images of Change: an archaeology of England's contemporary landscape(English Heritage).* Historic England, pp. 29.

[56] Cooper, M., 2015. Out Ultimate Guide to BISF Houses. [Online] Available at: https://www.homesellingexpert.co.uk/guides/ultimate-guide-to-bisf-houses#:~:text=BISF%20(British%20Iron%20and%20Steel,poor%20insulation%20and%20limited%20appeal [Accessed 2020].

[57] Zha, X. F. & Sriram, R. D., 2006. Platform-based porduct design and development: A Knowledge-intensive support approach. *Knowledge-Based System*, 19(7), pp. 524-543.

[58] D'Oca, S., Ferrante, A., Ferrer, C., Pernetti, R., Gralka, A., Sabastian, R. & Veld, P. O., 2018. Technical, Financial, and Social Barriers and Challenges in Deep Building Renovation: Integration of Lessons Learned from the H2020 Cluster Projects. *Buildings*, 8(12), pp. 174.

[59] Cooper, M., 2015. *Laing Easiform Houses: The Complete Guide*. [Online] Available at: https://www.homesellingexpert.co.uk/guides/laing-easiform-houses-complete-guide [Accessed 2020].

[60] Kivlehan, N. P., 2022. *Buildings that elevated cities.* [Online] Available at: https://ww3.rics.org/uk/en/modus/built-environment/commercial-real-estate/buildings-that-elevated-cities-wainwright-st-louis.html#:~:text=Standing%2010%2Dstoreys%20high%2C%20with,use%20of%20steel%20frame%20construction.[Accessed 2022].

[61] Rocha, P. F., Ferreira, N. O., Pimenta, F. & Pereira, N. B., 2023. Impacts of Prefabrication in the Building Construction Industry. *Encyclopedia,* 3(1), pp. 28-45.

[62] Winton, A. G., 2007. *The Bauhaus, 1919–1933. In Heilbrunn Timeline of Art History. New York: The Metropolitan Museum of Art, 2000–.* [Online] Available at: http://www.metmuseum.org/toah/hd/bauh/hd_bauh.htm.[Accessed 2024]

[63] Wang, Z., Chen, L., Zhao, X. & Zhou, W., 2014. Modularity in building mass customization capability: The mediating effects of customization knowledge utilization and business process improvement. *Technovation,* 34(11), pp. 678-687.

[64] Zhao, S., Zhang, Q., Peng, Z. & Lu, X., 2022. Product platform configuration for product families: Module clustering based on product architecture and manufacturing process. *Advanced Engineering Informatics,* Volume 52, pp. 101622.

[65] Miguel, P. A. C., 2005. Modularity in product development: a literature review towards a research agenda. *Product: Management & Devlopment,* 3(2), pp. 165-174.

[66] Friedman, B. G., 2020. *What is Modular Design?.* [Online] Available at: https://brettgfriedman.medium.com/what-is-modular-design-10d48920dbd4[Accessed 2020].

[67] Ho, M., Lai, J. H., Hou, C. & Zhang, D., 2021. Key Performance Indicators for Evaluation of Commercial Building Retrofits: Shortlisting via an Industry Survey. *Energies,* 14(21), pp. 7327.

[68] Luther, M. & Rajagopalan , P., 2014. Defining and developing an energy retrofitting approach. *Journal of Green Building,* 9(3), pp. 151-162.

[69] RISE, 2024. *Retrofit project overview: Toolkit.* [Online] Available at: https://riseretrofit.org.uk/storage/uploads/1722615503_Retrofit_Project_Overview_Toolkit.pdf#:~:text=Project%20preparation%20–%20all%20the%20actions%20required,upgrades%2C%20performance%20monitoring%2C%20and%20long%2D%20term%20maintenance.[Accessed 2024].

[70] Oliveria, C. C. d., Vaz, I. C. M. & Ghisi, E., 2024. Retrofit strategies to improve energy efficiency in buildings: An integrative review. *Energy and Buildings,* Volume 321, pp. 114624.

[71] Pombo, O., Rivela, B. & Neila, J., 2016. The challenge of sustainable building. *Journal of Cleaner Production,* Volume 123, pp. 88-100.

[72] Alexakis, K., Komninou, S., Kokkinakos, P. & Askounis, D., 2025. Climate-Sensitive Building Renovation Strategies: A Review of Retrofit Interventions Across Climatic and Building Typologies. *Sustainability,* 17(8), pp. 8187.

[73] Aloshan, M. A., 2025. Achieving near-zero energy in hot climates: Retrofitting building envelopes for existing homes. *Heliyon,* 11(3), pp. e42170.

[74] Zhou, Z., Zhang, S., Wang, C., Zuo, J., He, Q. & Rameezdeen, R., 2016. Achieving energy ef cient buildings via retrofitting of existing buildings: a case study. *Journal of Cleaner Production,* Volume 113, pp. 3605-3615.

[75] Refnier, C., Mathew, P., Shackelford, J., Lee, S.H., Robinson, A. & Walter, T., 2022. Multi-technology building system retrofits for utility incentive programs: Savings, costs and baseline considerations. *Energy and Buildings,* Volume 270, pp. 112270.

[76] Royapoor, M. & Roskilly, T., 2015. Building model calibration using energy and environmental data. *Energy and Buildings,* Volume 94, pp. 109-120.

[77] Ali, S., Abuhmed, T., El-Sappagh, S., Muhammad, K., Alonso-Moral, J., Confalonieri, R., Guidotti, R., Ser., J. D., Rodriguez, N. D. & Herrera, F., 2023. Explainable Artificial Intelligence (XAI): What we know and what is left to attain Trustworthy Artificial Intelligence. *Information Fusion,* Volume 99, pp. 101805.

[78] Zhou, Q., Wang, S. & Ma, Z., 2009. A model-based fault detection and diagnosis strategy for HVAC systems. *International Journal of Energy Research,* 33(10), pp. 903-918.

[79] Kim, S., 2025. Prefabricated and Modularized Residential Construction: A Review of Present Status, Opportunities, and Future Challenges. *Buildings ,* 15(16), pp. 2889.

[80] Mirzaei, P. A., Paterna, E. & Carmeliet, J., 2014. Investigation of the role of cavity airflow on the performance of building-integrated photovoltaic panels. *Solar Energy,* Volume 107, pp. 510-522.

[81] Li, J., Cai, Q., Wang, X., Liu, F., Yu, H., Liu, J., Miao, J., Li, G., Chen, T., Feng, L. & Zhang, J., 2024. Performance study of ventilated energy-productive wall: Experimental and numerical analysis. *Solar Energy,* Volume 273, pp. 113512.

[82] Bhamare, D. K., Rathod, M. K., Banerjee, J. & Arici, M., 2023. Investigation of the Effect of Air Layer Thickness on the Thermal Performance of the PCM Integrated Roof. *Buildings,* 13(2), pp. 488.

[83] Dahal, U. & Krarti, M., 2025. Thermal Impacts of Air Cavities Associated with Insulated Panels Deployed for Exterior Building Envelope Assemblies. *Energies,* 18(13), pp. 3573.

[84] Vanaga, R., Narbuts, J., Zundans, Z. & Blumberga, A., 2023. On-site testing of dynamic facade system with the solar energy storage. *Energy,* Volume 283, pp. 128257.

[85] Bocaneala, N., Mayouf, M., Vakaj, E. & Shelbourn, M., 2025. Artificial Intelligence Based Methods for Retrofit Projects: A Review of Applications and Impacts. *Archives of Computational Methods in Engineering,* Volume 32, pp. 899-926.

[86] Datta, S. D. et al., 2024. Artificial intelligence and machine learning applications in the project lifecycle of the construction industry: A comprehensive review. *Heliyon,* 10(5), pp. e26888.

[87] European Commission, 2014-2020. *Horizon 2020.* [Online]
Available at: https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-2020_en[Accessed 2023]

[88] House Energy, 2022. *Insulation Materials are Rated by Their R-Value or by Their U-Value.* [Online]
Available at: https://www.house-energy.com/Insulation/R-value-insulation.htm. [Accessed 2022]

[89] Ultimate Coatings LTD., 2023. *Air Tightness Regulations in the UK 2023.* [Online]
Available at: https://ultimatecoatings.co.uk/technology/air-tightness-regulations-in-the-uk-what-you-need-to-know/ [Accessed 2019].

[90] PLUG-N-HARVEST, 2017. *H2020-PLUG-N-play passive and active multi-modal energy HARVESTing systems, circular economy by design, with high replicability for Self-sufficient Districts Near-Zero Buildings.* [Online]
Available at: https://cordis.europa.eu/project/id/768735[Accessed 2019].

[91] 4RinEU, 2016. *H2020-Robust and Reliable technology concepts and business models for triggering deep Renovation of Residential buildings in EU.* [Online]
Available at: https://cordis.europa.eu/project/rcn/205647_en.html.[Accessed 2019].

[92] BERTIM, 2015. *H2020-Building energy renovation through timber prefabricated modules.* [Online]
Available at: https://cordis.europa.eu/project/rcn/196760_en.html.[Accessed 2019].

[93] ADAPTIWALL, 2013. *H2020-Multi-functional light-weight WALL panel based on ADAPTive Insulation and nanomaterials for energy efficient buildings.* [Online]
Available at: https://cordis.europa.eu/project/id/608808/reporting/es[Accessed 2019].

[94] A2pbeer, 2013. *H2020-Affordable and Adaptable Public Buildings through Energy Efficient Retrofitting.* [Online]
Available at: https://cordis.europa.eu/project/id/609060/reporting[Accessed 2019].

[95] BRESEAR, 2015. *H2020-Breakthrough solutions for adaptable envelopes for building refurbishment.* [Online]
Available at: https://cordis.europa.eu/project/rcn/193471_en.html.[Accessed 2019].

[96] E2VENT, 2015. *H2020-Energy Efficient Ventilated Façades for Optimal Adaptability and Heat Exchange enabling low energy architectural concepts for the refurbishment of existing buildings.* [Online]
Available at: https://cordis.europa.eu/project/rcn/193476/factsheet/[Accessed 2019].

[97] EnergyMatching, 2017. *H2020-Adaptable and adaptive RES envelope solutions to maximise energy harvesting and optimize EU building and district load matching.* [Online]
Available at: https://cordis.europa.eu/project/rcn/211462[Accessed 2019].

[98] Envision, 2017. *H2020-ENergy harVesting by Invisible Solar IntegratiON in building skins.* [Online]
Available at: https://cordis.europa.eu/project/rcn/211446_en.html.[Accessed 2019].

[99] HEART, 2017. *H2020-Holistic Energy and Architectural Retrofit Toolkit.* [Online]
Available at: https://cordis.europa.eu/project/rcn/211645_en.html.[Accessed 2019].

[100] Heat4cool, 2016. *H2020-Smart building retrofitting complemented by solar assisted heat pumps integrated within a self-correcting intelligent building energy management system..* [Online]
Available at: https://cordis.europa.eu/project/rcn/207412/fact[Accessed 2019].

[101] HERB, 2012. *H2020-Holistic energy-efficient retrofitting of residential buildings.* [Online]
Available at: https://cordis.europa.eu/project/rcn/105487_en.html.[Accessed 2019].

[102] ImPRESS, 2015. *H2020-New Easy to Install and Manufacture PRE-Fabricated Modules Supported by a BIM based Integrated Design ProceSS.* [Online]
Available at: https://cordis.europa.eu/project/id/636717/reporting[Accessed 2019].

[103] INSPIRE, 2012. *H2020-Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems.* [Online]
Available at: https://cordis.europa.eu/project/id/314461/reporting[Accessed 2019].

[104] MEEFS RETROFITTING, 2012. *H2020-Multifunctional Energy Efficient Façade System for Building Retrofitting.* [Online]
Available at: https://cordis.europa.eu/project/rcn/102074_en.html.[Accessed 2019].

[105] MF-Retrofit, 2013. *H2020-Multifunctional facades of reduced thickness for fast and cost-effective retrofitting.* [Online]
Available at: https://cordis.europa.eu/project/id/609345[Accessed 2019].

[106] MORE-CONNECT, 2014. *H2020-Development and advanced prefabrication of innovative, multifunctional building envelope elements for MOdular REtrofitting and CONNECTions.* [Online]
Available at: https://cordis.europa.eu/project/rcn/193236_en.html[Accessed 2019].

[107] Pro-Get-One, 2017. *H2020-Proactive synergy of inteGrated Efficient Technologies on buildings' Envelopes.* [Online]
Available at: https://cordis.europa.eu/project/rcn/211296_en.[Accessed 2019].

[108] ReCOST2T, 2018. *H2020-Residential Retrofit assessment platform and demonstrations for near zero energy and CO2 emissions with optimum cost, health, comfort and environmental quality..* [Online]
Available at: https://cordis.europa.eu/project/rcn/213424_en.html.[Accessed 2019].

[109] REnnovates, 2015. *H2020-Flexibility Activated Zero Energy Districts.* [Online]
Available at: https://cordis.europa.eu/project/rcn/198375[Accessed 2019].

[110] RenoZEB, 2017. *H2020-Accelerating Energy renovation solution for Zero Energy buildings and Neighbourhoods.* [Online]
Available at: https://cordis.europa.eu/project/rcn/211310_en.html.[Accessed 2019].

[111] RETROKIT, 2012. *H2020-RetroKit - Toolboxes for systemic retrofitting.* [Online]
Available at: https://cordis.europa.eu/project/rcn/104534_en.html.[Accessed 2019].

[112] Cui, Z., Taiwo, O. L. & Aaron, P. M., 2024. An application of AHP and fuzzy entropy-TOPSIS methods to optimize upstream petroleum investment in representative African basins. *Scientific Reports,* Volume 14, pp. 6956.

[113] Omeiza, L. A., Abid, M., Dhanasekaran, A., Subramanian, Y., Raj, V., Kozak, K., Mamudu, U. & Azad, A. K., 2024. Application of solar thermal collectors for energy consumption in public buildings – An updated technical review. *Journal of Engineering Research,* 12(4), pp. 994-1010.

[114] Yu, Q., Caui, Y. & Liu, L., 2023. Assessment of the parameter sensitivity for the ORYZA model at the regional scale - A case study in the Yangtze River Basin. *Environmental Modelling & Software,* Volume 159, pp. 105575.

[115] Dosh, A. J. & Joshi, B., 2018. Comparative analysis of Apriori and Apriori with hashing algorithm. *International Research Journal of Engineering and Technology (IRJET) ,* 05(01), pp. 976-979.

[116] La, F., 2018. Market Basket Analysis. *Artificially Intelligent,* 33(12).

[117] European Commission. *Horizon 2020.* [Online] Available at: https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-2020_en[Accessed 2019].

[118] Grove, J., 2011. *'Triple miracle' sees huge rise in EU funds for frontier research,* [Online] Available at: https://www-g.eng.cam.ac.uk/nms/highlights-press/2011-THE-interview.pdf.[Accessed 2019].

[119] Fereidoni, S., Nabisi, M., Fereidooni, L., Javidmehr, M., Zirak, N. & Kasaeian, A., 2023. An assessment of the impact of building envelope design on the tradeoff between embodied and operating energy. *Energy and Buildings,* Volume 298, pp. 113542.

[120] Hailu, G., 2021. 8 - Energy systems in buildings. In: Diez, D. B. & Asensio, E. R. eds. *Energy Services Fundamentals and Financing.* London:Academic Press, pp. 181-209.

[121] Rivera, A. C., Ochoa, W., Larrinaga, F. & Lasa, G., 2022. How-to conduct a systematic literature review: A quick guide for computer science research. *MethodsX,* Volume 9, pp. 101895.

[122] Li, Y., Du, H. & Kumaraswamy, S. B., 2024. Case-based Reasoning Approach for Decision-making in Building Retrofit: A Review. *Building and Environment,* Volume 248, pp. 111030.

[123] Chen, L. & Li, Y., 2021. A state-of-art method for solar irradiance forecast via using fisheye lens. *International Journal of Low-Carbon Technologies,* 16(2), pp. 555–569.

[124] Li, Y. & Chen, L., 2020. A study on database of modular façade retrofitting building envelope. *Energy and Buildings,* Volume 214, pp. 109826.

[125] Mantaras, R. L. D., McSherry, D., Bridge, D. & Leake, D., 2005. Retrieval, reuse, revision and retention in case-based reasoning. *The Knowledge Engineering Review*, 20(3), pp. 215-240.

[126] Czmoch, I. & Pekala, A., 2014. Traditional Design versus BIM Based Design. *Procedia Engineering,* Volume 91, pp. 210-215.

[127] Dabous, S. A. & Hosny, F., 2025. A review of building envelope retrofitting methods for improving energy efficiency, aesthetic, and indoor environmental quality. *Energy Nexus,* Volume 18, pp. 100407.

[128] Bruce Precious, 2022. *NABERS--Energy efficiency in commercial buildings.* [Online]
Available at:
https://www.nabers.gov.au/sites/default/files/energy_efficiency_in_commercial_buildings_full_length_guide.pdf[Accessed 2022].

[129] Finnie, F. & Sun, Z., 2003. R5 model for case-based reasoning. *Knowledge-Based Systems,* 16(1), pp. 59-65.

[130] Glew, D., Farmer, D., Miles-Shenton, D., Thomas, R., Fletcher, M., Hardy, A. & Gorse, C., 2021. *Thin Internal Wall Insulation (TIWI) Measuring Energy Performance Improvements in Dwellings Using Thin Internal Wall Insulation: Literature Review Appendix A.* [Online]
Available at:
https://assets.publishing.service.gov.uk/media/606c3301e90e074e4e4e864b/tiwi-annex-b.pdf[Accessed 2021].

[131] Global Status Report 2017, 2017. *Why the building sector?.* [Online]
Available at: https://architecture2030.org/why-the-building-sector/[Accessed 2018].

[132] International Energy Agency, 2021. *Energy Strategy 2050.* [Online]
Available at: https://www.iea.org/policies/5122-energy-strategy-2050[Accessed 2021].

[133] U.S. Census Bureau, 2018. *US Census Bureau Construction Spending Survey, U.S. Department of Commerce.* [Online]
Available at:
https://www.census.gov/construction/c30/historical_data.html.[Accessed 2018].

[134] Du, H., Huang, P. & Jones, P., 2019. Modular facade retrofit with renewable energy technologies: The definition and current status in Europe. *Energy and Buildings,* Volume 205, pp. 109543.

[135] Mavromatidis, L. E., Bykalyuk, A. & Lequay, H., 2013. Development of polynomial regression models for composite dynamic envelopes' thermal performance forecasting. *Applied Energy,* Volume 104, pp. 379-391.

[136] Roberti, F., Oberegger, U. F., Lucchi, E. & Troi, A., 2017. Energy retrofit and conservation of a historic building using multi-objective optimization and an analytic hierarchy process. *Energy and Buildings,* 138(1), pp. 1-10.

[137] Jafari, A. & Valentin, V., 2017. An optimization framework for building energy retrofits decision-making. *Building and Environment,* Volume 115, pp. 118-129.

[138] Gahrooei, M. R., Zhang, Y., Ashuri, B. & Augenbroe, G., 2016. Timing residential photovoltaic investments in the presence of demand uncertainties. *Sustainable Cities and Society,* Volume 20, pp. 109-123.

[139] Ma, D., Li, X., Lin, B. & Zhu, Y., 2023. An intelligent retrofit decision-making model for building program planning considering tacit knowledge and multiple objectives. *Energy,* 263(Part B), pp. 125704.

[140] Deb, C. & Schlueter, A., 2021. Review of data-driven energy modelling techniques for building retrofit. *Renewable and Sustainable Energy Reviews,* Volume 144, pp. 110990.

[141] Ma, Z., Cooper, P., Daly, D. & Ledo, L., 2012. Existing building retrofits: Methodology and state-of-the-art. *Energy and Buildings,* Volume 55, pp. 889-902.

[142] Kling, R. E., 1971. A Paradigm for Reasoning by Analogy. *Artificial Intelligence,* 2(2), pp. 147-178.

[143] Kolodner, J. L., 1992. An Introduction to Case-based Reasoning. *Artificial Intelligence Review,* 6(1), pp. 3-34.

[144] Perner, P., 1999. Using CBR learning for the low-level and high-level unit of an image interpretation system. *International Conference on Advances in Pattern Recognition,* pp. 45-54.

[145] Hamza, H., Belaïd, Y. & Belaïd, A., 2007. A Case-Based Reasoning Approach for Invoice Structure Extraction. *Ninth International Conference on Document Analysis and Recognition (ICDAR 2007),* Volume 1, pp. 327-331.

[146] Zahed, N., Najib, M. S. & Azhani, N.F.N.N.M, 2016. Classification of honey odor-profile using case-based reasoning technique (CBR). *ARPN Journal of Engineering and Applied Sciences,* 11(10), pp. 6675-6679.

[147] Nilsson, M. & Sollenborn, M., 2004. Advancements and Trends in Medical Case-Based Reasoning: An Overview of Systems and System Development. *Proceedings of the SeventeenthInternational Florida Artificial Intelligence Research Society Conference,* pp. 178-183.

[148] Holt, A., Bichindaritz, I., Schmidt, R. & Perner, P., 2005. Medical applications in case-based reasoning. *The Knowledge Engineering Review,* 20(3), pp. 289-292.

[149] Bichindaritz, I., 2008. Case-Based Reasoning in the Health Sciences: Why It Matters for the Health Sciences and for CBR. *Advances in Case-Based Reasoning,* Volume 5239, pp. 1-17.

[150] Pusztová, Ľ., Babič, F., Paralič, J. & Paraličová, Z., 2019. How to Improve the Adaptation Phase of the CBR in the Medical Domain. *Machine Learning and Knowledge Extraction,* Volume 11713, pp. 168-177.

[151] Sappagh, S. E. & Elmogy, M. M., 2016. Medical case based reasoning frameworks: Current developments and future directions. *International Journal of Decision Support System Technology,* 8(3), pp. 31-62.

[152] Matthew, S., 2010. *The century makers: 1945.* [Online]
Available at: https://www.telegraph.co.uk/property/newhomes/3318114/The-century-makers-1945.html[Accessed 2010].

[153] Asad, E., da Silva, M. G., Antunes, C. H. & Dias, L., 2012. Multi-objective optimization for building retrofit strategies: A model and an application. *Energy and Buildings,* Volume 44, pp. 81-87.

[154] Ahn, J., Ji, S., Ahn, S. J., Park, M., Lee, H., Kwon, N., Lee, E. & Kim, Y., 2020. Performance evaluation of normalization-based CBR models for improving construction cost estimation. *Automation in Construction,* Volume 119, pp. 103329.

[155] Fu, Y. & Shen, R., 2004. GA based CBR approach in Q&A system. *Expert Systems with Applications,* 26(2), pp. 167-170.

[156] Méndez, J. R., González, C., Glez-Peña, D., Riverola, F. F., Díaz, F. & Corchado, J. M., 2007. Assessing classification accuracy in the revision stage of a CBR spam filtering system.. *Case-Based Reasoning Research and Development, 7th International Conference on Case-Based Reasoning, ICCBR 2007. Volume 4626.* Berlin, Heidelberg: Springer.

[157] Ji, C., Hong, T. & Hyun, C., 2010. CBR revision model for improving cost prediction accuracy in multifamily housing projects. *Journal of Management in Engineering,* 26(4), pp. 229-236.

[158] Guo, Y., Hu, J. & Peng, Y., 2011. Research on CBR system based on data mining. *Applied Soft Computing,* 11(8), pp. 5006-5014.

[159] UK Climate Change Act 2008, 2009. *Climate Change Act 2008.* [Online] Available at: https://www.legislation.gov.uk/ukpga/2008/27/contents[Accessed 2019].

[160] Saaty, T. L., 1994. How to make a decision: the analytic hierarchy process.. *Interfaces,* 24(6), pp. 19-43.

[161] Leake, D. B., 1994. Case-based reasoning. *The Knowledge Engineering Review,* 9(1), pp. 61-64.

[162] Agrawal, R. & Srikant, R., 1994. Fast algorithms for mining association rules. *Proceedings of the 20th International Conference on Very Large Data Bases,* pp. 487-499.

[163] Alonso, J. A. & Lamata, M. T., 2006. Consistency in the Analytic Hierarchy Process: A New Approach. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems,* 14(4), pp. 445-459.

[164] Saaty, T. L., 2008. Decision Making with the analytic hierarchy process. *Int. J. Services Sciences,* 1(1), pp. 83-98.

[165] Dagdeviren, M., Yavuz, S. & Kilinc, N., 2009. Weapon selection using AHP and TOPSIS. *Expert Systems with Applications,* 36(4), pp. 8143-8151.

[166] Bullock, N., 2002. *Building the Post-War World: Modern Architecture and Reconstruction in Britain.* 1st Edition ed. London.:Routledge.

[167] Town and Country Planning Association, 2018. *Planning 2020 - Final Report of the Raynsford Review of Planning in England.* [Online] Available at: https://tcpa.org.uk/wp-content/uploads/2022/03/Planning-2020-Raynsford-Review-of-Planning-in-England-Final-Report.pdf [Accessed 2019].

[168] Harrison, J., 2020. Retrofitting Shallow-Pitch Roofs in Post-War Prefabs. *Energy and Buildings,* Volume 215, pp. 109876.

[169] Goodman, D. C. & Chant, C., 1999. *European cities & technology: industrial to post-industrial city.* London: Routledge.

[170] Davis, C., 2005. *The Prefabricated Home.* London: Reaction books Ltd.

[171] HI Resources, 2010. *Non Traditional Buildings.* [Online]
Available at: http://ww1.hiresources.co.uk/?sub1=6fc92182-db00-11eb-8111-a85a801f238f[Accessed 2011].

[172] Sassine, E., Kinab, E., Cherif, Y., Antczak, E. & Nasrallah, M., 2021. Thermal Performance of Lightweight Concrete Applications in Building Envelopes in Lebanon. *Building Thermal, Lighting and Acoustics Modeling*, Volume 14, pp. 1359-1375.

[173] Ghosh, S., 2024. *Cavity Walls: An Insight into Construction, Advantages, and Applications.* [Online]
Available at: https://dwello.in/news/cavity-walls-an-insight-into-construction-advantages-and-applications[Accessed 2024].

[174] Buildings Research Establishment-BR153, 1989. *Buildings Research Establishment (BRE): The structural condition of Wimpey no-fines low-rise dwellings.* London: BRE Press.

[175] Ford, H., 2020. *My Life and Work.* U.S..:Neeland Media LLC.

[176] Jose, A. & Tollenaere, M., 2005. Modular and platform methods for product family design: literature analysis. *Journal of Intelligent Manufacturing,* Volume 16, pp. 347-390.

[177] Kamali, M. & Kasun, H., 2016. Lifecycle Performance of Modular Buildings. *Automation in Construction,* Volume 71, pp. 163-74.

[178] Zhang, X. & Wei, P., 2020. Energy Efficiency in Modular Buildings. *Energy and Buildings,* Volume 207, pp. 109584.

[179] Pérez-Lombard, L., 2020. Overheating Risks in Insulated Buildings. *Applied Energy,* Volume 264, pp. 114702.

[180] Olsson, S., Malmqvist, T. & Glaumann, M., 2016. An approach towards sustainable renovationd A tool for decision support in early project stages. *Building and Environment,* Volume 106, pp. 20-32.

[181] Boxer, E., Henze, G. P. & Hirsch, A. I., 2017. A model-based decision support tool for building portfolios under uncertainty. *Automation in Construction,* Volume 78, pp. 34-50.

[182] Ahmada, T., Aibinua, A. & Thaheemb, M. J., 2017. BIM-based iterative tool for sustainable building design: A conceptual framework. *Procedia Engineering,* Volume 180, pp. 782 – 792.

[183] Nik-Bakht, M., Panizza, R. O., Hudon, P., Chassain, P.Y. & Bashari, M., 2020. Economy-energy trade off automation – A decision support system for building design development. *Journal of Building Engineering,* Volume 30, pp. 101222.

[184] Haruna, A., Shafiq, N. & Monstasir, O. A., 2021. Building information modelling application for developing sustainable building (Multi criteria decision making approach). *Ain Shams Engineering Journal,* 12(1), pp. 293-302.

[185] Cecconi, R., Moretti, F. N. & Tagliabue, L. C., 2019. Application of artificial neutral network and geographic information system to evaluate retrofit potential in public school buildings.. *Renewable and Sustainable Energy Reviews,* Volume 110, pp. 266-277.

[186] Amer, M., Hamdy, M., Wortmann, T., Mustafa, A. & Attia, S., 2020. Methodology for design decision support of cost-optimal zero-energy lightweight construction. *Energy & Buildings,* Volume 223, pp. 110170.

[187] Khansari, N. & Hewitt, E., 2020. Incorporating an agent-based decision tool to better understand occupant pathways to GHG reductions in NYC buildings. *Cities,* Volume 97, pp. 102503.

[188] Cheng, J. C. & Ma, L. J., 2015. A non-linear case-based reasoning approach for retrieval of similar cases and selection of target credits in LEED projects. *Building and Environment,* 11, Volume 93, pp. 349-361.

[189] Wang, J., Shen, L., Ren, Y., Ochoa, J.J., Guo, Z., Yan, H. & Wu, Z., 2019. A lessons mining system for searching references to support decision making towards sustainable urbanization. *Journal of Cleaner Production,* 209(1), pp. 451-460.

[190] Chen, W. T., Chang, P.-Y., Chou, K. & Mortis, L. E., 2010. Developing a CBR-based adjudication system for fatal construction industry occupational accidents. Part I: Building the system framework. *Expert Systems with Applications,* 37(7), pp. 4867-4880.

[191] Pohekar, S. D. & Ramachandra, M., 2004. Application of multi-criteria decision making to sustainable energy planning—A review. *Renewable and Sustainable Energy Reviews,* 8(4), pp. 365-381.

[192] An, S.-H., Kim, G.-H. & Kang, K.-I., 2007. A case-based reasoning cost estimating model using experience by analytic hierarchy process. *Building and Environment,* 42(7), pp. 2573-2579.

[193] Goodacre, C., Sharples, S. & Smith, P., 2002. Integrating energy efficiency with the social agenda in sustainability. *Energy and Buildings,* 34(1), pp. 53-61.

[194] Delgarm, N., Sajadi, B., Kowsary, F. & Delgarm, S., 2016. Multi-objective optimization of the building energy performance: A. *Applied Energy,* 170(15), pp. 293-303.

[195] Figueiredo, K., Pierott, R., Hammad, A. W. & Haddad, A., 2021. Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP. *Building and Environment,* Volume 196, pp. 107805.

[196] Akaa, O. U., Abu, A. & Spearpoint, M., 2020. A case study of design decision-making for an exemplar steel portal-framed building under fire exposure using a hybrid analysis technique. *Journal of Building Engineering,* Volume 28, pp. 101093.

[197] Leake, D. B., 2001. Problem Solving and Reasoning: Case-based. In: *International Encyclopedia of the Social & Behavioral Sciences.* Pergamon: Elsevier Ltd., pp. 12117-12120.

[198] Zhao, X., Tan, Y., Shen, L., Zhang, G. & Wang, J., 2019. Case-based reasoning approach for supporting building green retrofit decisions. *Building and Environment,* Volume 160, pp. 106210.

[199] Mejjaouli, S. & Alzahrani, M., 2020. Decision-making model for optimum energy retrofitting strategies in residential buildings. *Sustainable Production and Consumption,* Volume 24, pp. 211-218.

[200] Gercek, M. & Arsan, Z. D., 2019. Energy and environmental performance based decision support process for early design stages of residential buildings under climate change. *Sustainable Cities and Society,* Volume 48, pp. 101580.

[201] William, M. A., Suárez-López, M. J., Soutullo, S. & Hanafy, A. A., 2021. Building envelopes toward energy-efficient buildings: A balanced multi-approach decision making. *International Journal of Energy Research,* 45(15), pp. 21096-21113.

[202] Mosalama, K. M., Alibrandi, U., Lee, H. & Armengou, J., 2018. Performance-based engineering and multi-criteria decision analysis for sustainable and resilient building design. *Structural Safety,* Volume 74, pp. 1-13.

[203] Ren, F., Wei, Z. & Zhai, X., 2021. Multi-objective optimization and evaluation of hybrid CCHP systems for different building types. *Energy,* Volume 215, pp. 119096.

[204] Mukhamet, T., Kobeyev, S., Nadeem, A. & Memon, S. A., 2021. Ranking PCMs for building façade applications using multi-criteria decision-making tools combined with energy simulations. *Energy,* Volume 215, pp. 119102.

[205] Sánchez-Garrido, A. J., Navarro, I. J. & Yepes, V., 2022. Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction. *Journal of Cleaner Production,* Volume 330, pp. 129724.

[206] Gade, A. N., Larsen, T. S., Nissen, S. B. & Jensen, R. L., 2018. REDIS: A value-based decision support tool for renovation of building portfolios. *Building and Environment,* Volume 142, pp. 107-118.

[207] Laguna Salvadó, L., Villeneuve, E. & Masson, D., 2019. Decision Making in Near Zero Energy Building Refurbishment: A Technology Alternatives Ranking Tool. *IFAC PapersOnLine,* 52(13), pp. 313-318.

[208] Moghtadernejad, S., Chouinard, L. E. & Mirza, M. S., 2020. Design strategies using multi-criteria decision-making tools to enhance the performance of building façades. *Journal of Building Engineering,* Volume 30, pp. 101274.

[209] Ruggeri, A. G., Calzolari, M., Scarpa, M., Gabrielli, L. & Davoli, P., 2020. Planning energy retrofit on historic building stocks: A score-driven decision support system. *Energy and Buildings,* Volume 224, pp. 110066.

[210] Mirjalili, S., 2019. *Evolutionary algorithms and neural networks: theory and applications.* Cham, Switzerland: Springer.

[211] She, C., Jia, R., Hu, B., Zheng, Z., Xu, Y. & Rodriguez, D., 2021. Life cycle cost and life cycle energy in zero-energy building by multi-objective optimization. *Energy Reports,* Volume 7, pp. 5612-5626.

[212] Yadegaridehkordi, E., Hourmand, M., Nilashi, M., Alsolami, E., Samad, S., Mahmoud, M., Alarood, A.A., Zainol, A., Majeed, H.D. & Shuib, L., 2019. Assessment of sustainability indicators for green building manufacturing using fuzzy multi-criteria decision making approach. *Journal of Cleaner Production,* Volume 277, pp. 122905.

[213] Abedi, M., Torabi, S.A., Norouzi, G., Hamzeh, M. & Elyasi, G., 2012. PROMETHEE II: A knowledge-driven method for copper exploration. *Computers and Geosciences,* Volume 46, pp. 255-263.

[214] Beccali, M., Ciulla, G., Brano, V. L., Galatioto, A. & Bonomolo, M., 2017. Artificial neural network decision support tool for assessment of the energy performance and the refurbishment actions for the non-residential building stock in Southern Italy. *Energy,* Volume 137, pp. 1201-1218.

[215] Liu, B. & Rodriguez, D., 2021. Renewable energy systems optimization by a new multi-objective optimization technique: A residential building. *Journal of Building Engineering,* Volume 35, pp. 102094.

[216] He, M., Brownlee, A., Lee, T., Wright, J. & Taylor, S., 2015. Multi-objective optimization for a large scale retrofit program for the housing stock in the North East of England. *Energy Procedia,* Volume 78, pp. 854-859.

[217] Lan, L., Wood, K. L. & Yuen, C., 2019. A holistic design approach for residential net-zero energy buildings: A case study in Singapore. *Sustainable Cities and Society,* Volume 50, pp. 101672.

[218] Naderi, E., Sajadi, B., Behabadi, M. A. & Naderi, E., 2020. Multi-objective simulation-based optimization of controlled blind specifications to reduce energy consumption, and thermal and visual discomfort: Case studies in Iran. *Building and Environment,* Volume 169, pp. 106570.

[219] Martínez, S., Pérez, E., Eguía, P., Erkoreka, A. & Granada, E., 2020. Model calibration and exergoeconomic optimization with NSGA-II applied to a residential cogeneration. *Applied Thermal Engineering,* Volume 169, pp. 114916.

[220] Zhang, M.L. & Zhou, Z.H., 2007. ML-KNN: A lazy learning approach to multi-label learning. *Pattern recognition,* 40(7), pp. 2038-2048.

[221] Moghadam, S. T. & Lombardi, P., 2019. An interactive multi-criteria spatial decision support system for energy retrofitting of building stocks using CommuntiyVIZ to support urban energy planning. *Building and Environment,* Volume 163, pp. 106233.

[222] Sandanayake, M., Zhang, G. & Setunge, S., 2019. Estimation of environmental emissions and impacts of building construction – A decision making tool for contractors. *Journal of Building Engineering,* Volume 21, pp. 137-185.

[223] Juan, Y. K., Gao, P. & Wang, J., 2010. A hybrid decision support system for sustainable office building renovation and energy performance improvement. *Energy and Buildings,* 42(3), pp. 290-297.

[224] Asadi, E., Da Silva, M., Antunes, C. & Dias, L., 2012. Multi-objective optimization for building retrofit strategies: A model and an application.. *Energy and Buildings,* Volume 44, pp. 81-87.

[225] Roth, F. H. & Jacobstein, N., 1994. The state of knowledge-based systems. *Publication History,* 37(3), pp. 26-39.

[226] Ontañón, S. & Plaza, E., 2003. Collaborative Case Retention Strategies for CBR Agents. *Case-Based Reasoning Research and Development,* Volume 2689, pp. 392-406.

[227] Ahn, J., Ji, S., Park, M., Lee, H., Kim, S. & Suh, S., 2014. The attribute impact concept: Applications in case-based reasoning and parametric cost estimation. *Automation in Construction,* Volume 43, pp. 195-203.

[228] Faia, R., Pinto, T., Abrishambaf, O., Fernandes, F., Vale, Z. & Corchado, J. M., 2017. Case based reasoning with expert system and swarm intelligence to determine energy reduction in buildings energy management. *Energy and Buildings,* Volume 155, pp. 269-281.

[229] Wang, H.J., Chiou, C.W. & Juan, Y.K., 2008. Decision support model based on case-based reasoning approach for estimating the restoration budget of historical buildings. *Expert Systems with Applications,* 35(4), pp. 1601-1610.

[230] Chou, J.S., 2009. Web-based CBR system applied to early cost budgeting for pavement maintenance project. *Expert Systems with Applications,* 36(2), pp. 2947-2960.

[231] Shen, L., Yan, H., Fan, H., Wu, Y. & Zhang, Y., 2017. An integrated system of text mining technique and case-based reasoning (TM-CBR) for supporting green building design. *Building and Environment,* 11, Volume 124, pp. 388-401.

[232] Xiao, X., Skitmore, M. & Hu, X., 2017. Case-based Reasoning and Text Mining for Green Building Decision Making. *Energy Procedia,* 3, Volume 111, pp. 417-425.

[233] Ahn, J., Park, M., Lee, H., Ahn, S., Ji, S., Song, K. & Son, B., 2017. Covariance effect analysis of similarity measurement methods for early construction cost estimation using case-based reasoning. *Automation in Construction,* Volume 81, pp. 254-266.

[234] Okudan, O., Budayan, C. & Dikmen, I., 2021. A knowledge-based risk management tool for construction projects using case-based reasoning. *Expert Systems with Applications,* Volume 173, pp. 114776.

[235] Koo , C., Hong, T., Hyun, C, Park, S. & Seo, J., 2010. A study on the development of a cost model based on the owner's decision making at the early stages of a construction project. *International Journal of Strategic Property Management,* Volume 14, pp. 121-137.

[236] Koo, C., Hong, T. & Hyun, C., 2011. The development of a construction cost prediction model with improved prediction capacity using the advanced CBR approach. *Expert Systems with Applications,* 38(7), pp. 8597-8606.

[237] Hong, T., Koo, C. & Park, S., 2012. A decision support model for improving a multi-family housing complex based on CO2 emission from gas energy consumption. *Building and Environment,* Volume 52, pp. 142-151.

[238] Koo, C. & Hong, T., 2015. A dynamic energy performance curve for evaluating the historical trends in the energy performance of existing buildings using a simplified case-based reasoning approach. *Energy and Buildings,* 4, Volume 92, pp. 338-350.

[239] Hong, T., Koo, C., Kim, D., Lee, M. & Kim, J., 2015. An estimation methodology for the dynamic operational rating of a new residential building using the advanced case-based reasoning and stochastic approaches. *Applied Energy,* Volume 150, pp. 308-322.

[240] Kwon, N., Song, K., Ahn, Y., Park, M. & Jang, Y., 2020. Maintenance cost prediction for aging residential buildings based on case-based reasoning and genetic algorithm. *Journal of Building Engineering,* Volume 28, pp. 101006.

[241] Jung, S., Pyeon, J., Lee, H., Park, M., Yoon, I. & Rho, J., 2020. Construction Cost Estimation Using a Case-Based Reasoning Hybrid Genetic Algorithm Based on Local Search Method. *Sustainability,* 12(19), pp. 7920.

[242] Chang, S., Castro-Lacouture, D. & Yamagata, Y., 2020. Decision support for retrofitting building envelopes using multi-objective optimization under uncertainties. *Journal of Building Engineering,* Volume 32, pp. 101413.

[243] Liang, Y., Ashur, B. & Li, M., 2021. Forecasting the Construction Expenditure CashFlow for Transportation Design-Build Projectswith a Case-Based Reasoning Model. *Journal of Construction Engineering and Management,* Volume 147.6, pp. 04021043.

[244] Jin, R., Cho, K., Hyun, C. & Son, M., 2012. MRA-based revised CBR model for cost prediction in the early stage of construction projects. *Expert Systems with Applications,* 4, 39(5), pp. 5214-5222.

[245] Guerrero, J., Miró-Amarante, G. & Martín, A., 2022. Decision support system in health care building design based on case-based reasoning and reinforcement learning. *Expert Systems with Applications,* Volume 187, pp. 116037.

[246] Ji, S.H., Park, M. & Lee, H.S., 2011. Cost estimation model for building projects using case-based reasoning. *Canadian Journal of Civil Engineering,* Volume 38, pp. 570-581.

[247] Kim, K. J. & Kim, K., 2010. Preliminary Cost Estimation Model Using Case-Based Reasoning and Genetic Algorithms. *Journal of Computing in Civil Engineering,* 24(6), pp. 499-505.

[248] BuildHEART, 2015. *H2020-Standardised approaches and products for the systemic retrofit of residential Buildings, focusing on heating and cooling consumptions attenuation.* [Online]
Available at: https://cordis.europa.eu/project/id/680658[Accessed 2019].

[249] Shih, H.S., Shyur, H. J. & Lee, E. S., 2007. An extension of TOPSIS for group decision making. *Mathematical and Computer Modelling,* Volume 45, pp. 801-803.

[250] RIBA, 2020. *Plan of Work 2020 Overview.* [Online]
Available at: www.ribaplanofwork.com[Accessed 2020].

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Publications

[1] Li, Yangluxi, Hu Du, and Satish Basavapatna Kumaraswamy. "Case-based reasoning approach for decision-making in building retrofit: A review." *Building and Environment* 248 (2024): 111030.

[2] Li, Yangluxi, and Lei Chen. "A study on database of modular façade retrofitting building envelope." *Energy and Buildings*214 (2020): 109826.

[3] Li, Yangluxi, et al. "A Review of Artificial Intelligence Applications in Architectural Design: Energy-Saving Renovations and Adaptive Building Envelopes." *Energies* 18.4 (2025): 918.

[4] Li, Yangluxi, and Lei Chen. "Investigating of European modular façade system utilizing renewable energy." *International Journal of Low-Carbon Technologies* 17 (2022): 279-299.