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A systematic method of retrofit of urban residential buildings for design, decision and policymaking in Chongqing, China

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December 2022

A thesis submitted for the degree of Doctor of Philosophy

Abstract

Energy consumption and carbon emission have become a challenge in old residences in China. Old residential buildings remain dilapidated with their poorly insulated building façade and significant potential in energy and carbon conservation. Yet the current circumstances are found very complicated due to the unclear reality and complex nature of the diversities of building conditions, resident preferences, economy, and social factors of coordination and motivation. Retrofit of urban residential buildings (RURB) is treated not as a systematic research topic, but rather as a project-based construction process in current knowledge. This linear thinking has been argued which caused empiricism problems since interconnections between retrofit system participants are notably neglected.

To achieve the research objectives and justify the system thinking perspective, this thesis explores and understands the system cognition and interactions of the Retrofit of Urban Residential Buildings (RURB). The adopted system thinking method, interviews, and questionnaire survey methods are used based on causal layered analysis for the comprehensive system definition, boundary, variables, and participants. System interactions between system players and variables are also analysed by using the causal loop diagram method, hence systemic problems can be discovered. With this theoretical basis, a case study of the Chongqing city zone is selected to support the system theory with urban retrofit effects. Results of retrofitting benefits and costs are obtained through modelling, field survey, energy simulation, and calculation approaches. They are evaluated as five retrofit criteria of energy, cost, comfort, function, and safety improvements. A total of the six retrofit scenarios with four referencing building types are applied to multi-criteria decision-making analysis, as the analytic network process for the weighted values of retrofit benefits and costs. The retrofitting potential, solutions for systemic problems, and hence the suggestions for future policymaking are found and discussed. This research develops an innovative and coherent method to support future RURB decision-making and policymaking by providing both a theoretical basis and reliable data source, which can become a generalised approach to RURB analysis in other city conditions.

Declaration

I confirm that this is my own work and that the use of all material from other sources has been properly and fully acknowledged.

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December 2022

Acknowledgement

I would like to extend my greatest appreciation to the people who have helped me during my PhD period.

I would like to give my deepest gratitude to my first supervisor, Professor Runming Yao. Her magnificent knowledge, critical view, and extremely valuable support with her limitless patient have inspired, questioned, guided, and helped me to understand the whole process of academic doctorial research. Professor Runming was always professional and supportive providing useful and timely suggestions and comments in my reviewing, thinking and writing. She was always encouraging me to explore the knowledge of the built environment and to improve my skills and research abilities with her knowledge, passion and selfless contributions. She will be a lifelong mentor and friend of mine.

I would like to give my great thanks to Dr Emmanuel Essah for his advice of technical support during the case study and building simulation stage. His comprehensive and professional knowledge has supported me to achieve the rationality and reliability of this thesis. Dr Emmanuel has always been kind, skilled and patient to inspire me with his intelligent teaching and critical thinking from the time I was studying in Reading for my MSc degree, until the completion of this PhD thesis.

I am also grateful to those amazing colleagues who helped me in many respects. Thanks to Professor Zhiwen Luo and Dr Maria Vahdati, who always inspired me with passion and communication as my PhD assessors. Thanks to Professor Libby Schweber for her help and support in the school. Thanks to Dr Mehdi Shahrestani who generously shared his knowledge and kindness and gave me great advice. I am also grateful for the support from my friends, especially Dr Beibei Qin, Dr Lai Jiang, Wenbo Wang, and Xiaoxiong Xie.

I would also express my great appreciation to my family. My parents, brothers and sisters always support me with unconditional love, encouragement, and financial aid while I was studying and doing my research far away from home. I would never have been able to finish this thesis without the help of my family.

Abbreviation

AHP – Analytic Hierarchy Process

AHSP – Air Source Heat Pump

ANP – Analytic Network Process

APG – Adhesive Polystyrene Granule Mortar

BEES – Building Energy Efficiency Standards

BEM – Building Energy Modelling

CGBL – China Green Building Label

CLA – Causal Layered Analysis

CLD – Causal Loop Diagrams

DCLG - Department for Communities and Local Government (of England)

DDMR – Desire and Decision-Making of Retrofit

ECPRB -- Energy Conservation Policies of Residential Buildings

EMC - Energy Management Contract

EPC – Energy Performance Contracting

EPS – Expanded Polystyrene Board

EUI – Energy Use Intensity

FYP – The Five-Year Plan

GIS – Geographic Information System

GPEBE – Governmental Policies of Energy, Building and Environment

HSCW – Hot Summer and Cold Winter

HSWW – Hot Summer and Warm Winter

HVAC – Heating, Ventilation, and Air Conditioning

LED – Light Emitting Diode

Low-E – Low Emissivity Glazing

MAUT – Multi-Attribute Utility Theory

MCDM – Multi-Criteria Decision Making

MOHURD - Ministry of Housing and Urban-rural Development (of China)

OCI – Operating Cost Intensity

OECI – Operating Energy Consumption Intensity

PIC – Polyurethane Insulation Coating

PROMETHEE - Preference Ranking Organization Method for Enriched Evaluation

PVC – Polyvinyl Chloride

RED – Renewable Energy Directive

RIC – Reflection Insulation Coating

RICI- Retrofit Investment Cost Intensity

RIECI – Retrofit Investment Energy Consumption Intensity

ROIDF – Roles, Outputs, Issues, Demands, Features

RTC – Retrofit Time Cost

RURB – Retrofit of Urban Residential Building

RW – Rock Wool Board

SBS – Styrene-Butadiene-Styrene Asphalt

SC & C – Server Cold and Cold

SPA – System Player Analysis

SPSS - Statistical Product Service Solutions

TGPUG – Technical Guidelines of Passive, Ultra-low Energy Consumption and Green Buildings

TSNZE – Technical Standard for Nearly-Zero Energy building

UNFCCC - United Nations Framework Convention on Climate Change

XPS – Extruded Polystyrene Board

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1.1. Research context

1.1.1. The burden of increasing energy consumption in residential buildings

With the increasing energy scarcity and problems of climate change, the largest sector of energy consumption - buildings, take the most responsibility for their 30% proportion of total global energy consumption (International Energy Agency, 2021). In recent years of China, there are many newly issued sustainable concepts such as green buildings with advanced techniques in energy conservation, but few of them have been applied in existing building retrofitting (Zuo and Zhao, 2014). In this case, the existing residential buildings remain poorly insulated and old with low energy efficient design, equipment, and poor quality of built environment (Dunham-Jones and Williamson, 2008).

China is a representative case country for building retrofit research based on its characteristics and time of historical development. Recently, China has taken an incredible speed of development of economy and construction industries. For both the national development of sustainability and international responsibility for climate change, China has issued two significantly important national objectives of carbon emission peak and carbon neutrality (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2022a). The two objectives require the country to achieve 65% carbon emission reduction and energy conservation in the building sector in 2030. Therefore, it’s an urgent task for the country to retrofit old residential buildings because of the large stock number of old residences and energy-saving potential. Relatively, energy efficiency policies were developed quickly during the last two decades (Liu, 2019). However, in the building sector, the focus of the national government was argued (Han et al., 2021) which always lies on the energy efficiency of new buildings and public buildings, rather than old residences.

The very late start of energy conservation development of residential buildings in China brought back the fact that many existing buildings still were built with poor thermal performance materials and now remain low energy efficiency. China's national statistic for 2020 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2021) showed that China is currently having 687 cities with 442.53 million people living in the urban area, and the total residential building amount has been a massive number of 18,098 km^2 – 25% of them are very old with low building energy efficiency. These buildings have comparably poor performance, such as poor insulation levels (Yoshino et al., 2004), lack of heating or cooling equipment (Guo et al., 2015), and lack of sustainable designs (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2010b) due to the building standards of energy efficient in that time were issued without enough modern consideration of sustainability. This situation clearly states the importance to increase energy efficiency and reduce carbon emissions in the current building stock, which operating energy takes about 21.8% of total national energy consumption (China Association of Building Energy Efficiency, 2021).

In China, to achieve the reduction objective in energy conservation and carbon emission, it is urgently important that people need to start improving building energy efficiency and sustainability of their living houses, by extensively applying **Retrofitting of Urban Residential Buildings (RURB)**. From the statement of the most important national policy of the 11^{th} to 14^{th} Five-Years plans (National Development and Reform Commission, 2006, National Development and Reform Commission, 2011, National Development and Reform Commission, 2016, Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2022a), the importance of RURB has been frequently and increasingly mentioned as the mandatory governmental objectives. They presented a strong will to accelerate the development of RURB in a developing country, which brings the research opportunities of the relevant topics, and this thesis research.

1.1.2. The Unclear reality of RURB

The reality of RURB is currently unclear for both policymakers and city planners in China. For example, based on the high urbanization rate in China of 17.9% to 52.6% in the last two decades, an enormous number of residential buildings were built since 1978 in bad conditions (United Nations Development Programme, 2013). This long timeline of development has made the conditions and thermal performance of urban residential buildings very complicated. For policymakers, the bottom-up statistics can show them the total stock number of buildings, but they cannot obtain the accurate number for residential buildings, much less the number of ‘old’ residential buildings. Therefore, the stock number of old residences which require retrofit is unclear to policymakers.

More importantly, the building conditions and performance of old residences are also unclear to policymakers. Since building ageing is a dynamic process, it is difficult to justify the definition of ‘old residences’ due to the diversity of old levels, built age, building types, and building materials used. By reviewing the building design standards issued so far, there is no very clear official definition for old residences with an explicit index and description of building conditions. Only brief explanations were mentioned in the relevant standards stated such as ‘the residential buildings built around 1980 should be considered as very old residences’ (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2005), and ‘the residences built before 1998 with backward public facilities which affect the basic life of residents (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2022b), while both are not clear enough to satisfy the RURB policymakers and scholars. Therefore, a comprehensive definition of old residences should be justified to describe the different old residential building types with clear building index and parameters of building performance.

Negatively, because of the lack of available data to present the realistic situation of old residences, the national government meets their difficulty to issue the relevant policy for RURB. Hence the RURB designers and engineers are currently working with a very low efficiency since they do not have a reliable retrofit regulation or building retrofit design standard. As a result, it is inferred that a more effective and accurate approach to exploring and understanding the unclear reality of RURB is urgently required for future policymaking.

1.1.3. The complex nature of RURB

Although the Chinese governmental policymakers showed their positive desire to expedite the process, the RURB is an ambitious task due to its complex nature. For a country with a very large territory, different climate conditions, long development history, and complicated regional diversity of economy and culture, RURB is not only a linear issue of building engineering, but a mixture of social, economy, engineering, and well-being problems. These factors lead to incredibly diverse thermal comfort requirements, economic levels and building occupant behaviours along different residential building types and locations (Li et al., 2011).

Among these diversity problems, the social factor is the most difficult problem to be dealt with for RURB, as the coordination from residents who live in the old residences. In reality, both Chinese statistics and governmental reports (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2009, China Association of Building Energy Efficiency, 2016) showed that the RURB policy is extremely difficult to implement due to heavy denial from the building owners – the residents. For example, a speech given by the governmental officer Qiu (2019) has shown how difficult when the government wants to retrofit old residential communities – even installing a lift, could be surprisingly arguable and challengeable to achieve due to the diverse opinions and resistance from the residents in the same building. The confusion found by the government officers shows there are too many diverse concerns and problems among residents, and they cannot easily decide to retrofit their homes - these interfering factors are not fully understood and clarified (China Association of Building Energy Efficiency, 2016).

Another complex feature of RURB development is the conflict between energy consumption and comfort improvement. It is unavoidable to increase the total energy use and carbon emission while improving the indoor comfort level by increasing the usage frequency of heating, cooling, and other electronic devices. In this case, there are some contradictions between strict energy conservation objectives and a better indoor environment appearing while people pursue better living quality and the built environment. One remarkable example in China could be the request for the district heating system retrofit in southern China – it has been argued for many years that people who live in hot summer and cold winter climate zone asked for a similar district heating system as in northern China, to enjoy the warmer indoor thermal comfort during winter (Xinhua News Agency, 2015, Tsinghua University Building Energy Research Center, 2021). Although it is almost impossible and very inefficient to apply this system to the south due to too difficult retrofit engineering works will be needed (FinancePeople.com, 2014, Tsinghua University Building Energy Research Center, 2021), this request has still been argued until today, which shows how imperative the people are looking for a better living quality of their houses.

Therefore, the development of RURB must consider both sides of contradictions, as to reduce the energy consumption (governmental objectives raised by policymakers), and to increase indoor comfort (raw retrofit demands of residents). These two inconsistent objectives should be achieved simultaneously. This balance issue causes the nature of RURB to become even more complicated. It shows that the conventional thinking and research approaches of linear engineering work are not satisfied the purposes of modern RURB development.

1.2. Research questions

Following the current unclear reality and complex nature of RURB, it can be inferred that RURB has not been studied and understood as a whole system. People as professionals and residents involved in RURB are isolated from each other, while residents do not have completed knowledge and data to support their decision-making. Therefore, the first research question is raised:

1) **How should the system of retrofitting in urban residential buildings (RURB) be fully understood in China?**

Later, the causals and feedback between different people within the RURB system nature should be fully clarified and understood. However, different players may have diverse considerations for each system variable during the retrofit process due to their retrofit desire, opinions, and preferences. Therefore, an integrated and comprehensive research method with the ability to explore their interactions should be applied for this purpose for the third research question:

2) **What are the relationships between retrofit policies, designs, engineering works, retrofit techniques, retrofit benefits, and costs in China?**

Once both the reality and nature of RURB are clarified, the retrofit results should be analysed to obtain and explain benefits and costs, through appropriate retrofit designs. For all retrofit studies or projects, it is mandatory to evaluate the retrofit effects as 'before' and 'after' views. However, it is arguable that accurately presenting the 'before' all the residential buildings in the urban area is very challenging since there currently is no official definition of 'old residence'. Meanwhile, the 'after' view should be able to generate high-quality data for the evaluation of retrofit benefits and costs, but the possible retrofit plans can be various because of the differences in retrofit measures selected. Therefore, a case study should be developed as an experimental platform to support the defined RURB system, so the third research question is thus raised:

3) **How to obtain realistic and reliable data to describe the current conditions of old residences, and to evaluate the retrofit results?**

Once the retrofit designs and results have been acquired, it is necessary to analyse the retrofit criteria and find the most appropriate retrofit design for the specific retrofit demand. A proper data analysis and evaluation method should be applied as it is the final achievement to help retrofit decision-making and provide evidence to develop RURB policymaking. Accordingly, the fourth research question is raised:

4) **How to analyse the evidence acquired for RURB decision-making and policymaking based on multiple retrofit designs and result criteria?**

In summary, the first and second research questions should be answered by developing a RURB theory with a systematic perspective to comprehensively understand its system definition, cognition, and complex interactions between system entities and variables. The third and fourth research questions should be answered by establishing an appropriate research framework for RURB design and result analysis following the raised theoretical basis, as the answers of the previous two research questions.

1.3. Aim and objectives

Following the research questions raised, this research is going to explore the system cognition and interactions of RURB by developing a theoretical basis of system thinking perspective to obtain the evidence for RURB policymaking, design, and decision-making. A theoretical understanding of RURB with a system perspective should be developed by clarifying the system definition, and comprehensive RURB system cognition and interactions. Furthermore, a case study should be developed as an experimental platform to evidence the system theory based on appropriate methods of retrofit modelling and design. There are five research objectives with deliverables as follows:

1) To explore the current problems and research gaps in the knowledge of RURB policy content, academic studies hence to find the insights based on previous experience.

2) To clarify and understand the RURB system by systematically discovering and

analysing system cognition, system definition, boundary, elements, participants, and their characteristics.

3) To clarify and understand the complex system interactions with system variables, causal links, and feedback, and to find the hidden systemic problems in the current RURB system and relevant possible solutions for RURB design.
4) To develop a research framework to generate reliable data of retrofit results based on both the RURB system theoretical basis and realistic data, which should be collected from RURB professionals and residents, of their retrofit desires and demands, knowledge, retrofit designs with suitable retrofit measures, and individual opinions.
5) To evaluate the retrofit benefits and costs of the case study retrofitted results and make decisions for the retrofit plan designed for the local urban areas. According to the analysis of decision-making based on retrofit criteria, evidence and suggestions can be obtained to support more scientific future policymaking of RURB.

By applying RURB modelling and energy simulation methods, this research should be able to proceed with more scientific retrofit designs and produce more reliable data of retrofit effects, as 'different retrofit criteria' on an urban scale. Results are expected to be able to evaluate the urban retrofitting potential of benefits on energy, carbon, improvement of the indoor environment, and costs on energy, economy, and time. The research outcomes are expected to provide approaches for urban retrofitting progression and provide evidence for future policymaking, as well as to achieve energy conservation and living quality improvements from the old residential building sector.

1.4. Outline of the thesis structure

This section presented the structure of the thesis. The contribution of each chapter in turn is introduced below:

Chapter One is the introduction section of the thesis which the importance and current situation of RURB research are introduced and described. The RURB is found extremely important for policymakers to achieve national objectives in the energy and carbon sectors. However, two important issues of 'unclear reality' and 'complex nature' are identified based on the background information reviewed, which have hindered the development of modern RURB. This chapter aims to attract readers who have research interests of retrofit urban residential buildings and to raise and confirm the research questions and objectives.

Chapter Two reviews the existing literature with a critical view to understanding the current knowledge, knowledge gaps, and found problems of RURB. Three types of literature have been reviewed including the policy development history, current methods of academic studies, and completed engineering practices.

The literature review presents a grand picture of the RURB policy system in China, the widely-used research methods available for RURB, and the experiences and retrofit results provided by demonstration projects. The critiques of current knowledge have been discussed and the insights from the literature review have become valuable support for the later design of this thesis research.

Chapter Three presents and justifies the adopted research methodology as a means of answering the stated research questions and achieving the designed research objectives. Initially, the research strategy design with steps will be proposed based on the insights provided by existing literature reviewed to solve the current problems and fill the current knowledge gaps of RURB.

Thereafter, 'available methods for RURB' from academic studies in the field are reviewed for the selection of appropriate methods for this thesis research. System thinking approaches are argued to be suitable for the purposes of providing a rich description, definition, boundary, system elements, variables, causal links, and feedback to fully understand the RURB system cognition and interactions. The strategy of developing the case study and research techniques for data collection is later presented to verify the RURB system. Finally, research ethics issues and research originalities are discussed.

Chapter Four presents the process of justifying and clarifying the RURB system with its cognition and interactions, and the result of survey methods. This chapter is structured according to the identified steps argued from the selected system thinking theory, as (i) 'Justifying the hypothesis of RURB is a system', (ii) 'clarifying the system elements', (iii) acquiring the qualitative data from RURB professionals, (iv) acquiring the retrofit desires, opinions and preferences from residents, (v) applying an adopted system thinking analysis method for RURB system cognition, and (vi) identifying system interactions to find systemic problems. The result of this chapter provides a comprehensive understanding of ‘what is RURB system’, and ‘what is happening in the RURB system’. They are related to the first and second stated research questions, which can become the theoretical basis to support the future RURB research and policymaking, as well as the following case study section of this thesis.

Chapter Five develops a case study of urban areas to generate the data of retrofit results and investments, supported by the system thinking analysis results clarified in Chapter Four. The case study developed is similar to an experimental platform to evidence the argued RURB system cognition and interactions. In this chapter, the current building conditions of old residences are modelled based on the data from field surveys and documents.

Afterwards, the concept of retrofit criteria is proposed to analyse the relevant retrofit benefits and costs, such as energy, cost, comfort improvement, added building functions, and safety improvement. The methods of energy calculation, project budget, and building energy simulation corresponding to the defined RURB system are adopted to obtain the quantitative retrofit criteria.

Finally, the multi-criteria decision-making method is applied to evaluate the retrofit designs and generate suggestions for future RURB policymaking in the case study area, while the rationality and innovation of the developed RURB system concept are also validated.

Chapter Six discusses the findings of both Chapters Four and Five of the discovered systemic problems from RURB system cognition and interactions. Based on the theoretical basis developed by the SPA and CLD methods, the understanding, systemic problems, and possible solutions are revealed and discussed for the RURB system in China’s condition.

Afterwards, the benefit and cost analysis of retrofit criteria from the case study in Chongqing city is presented and discussed based on the energy simulation, calculation, and decision-making analysis results to reflect to the literature and current research gaps.

Chapter Seven is the conclusion chapter which concludes an overall summary of the thesis and addresses the achievements of the stated overarching research aim and research objectives. Importantly, the emphasis is focused on the contribution to the knowledge of RURB policymaking, research, and decision-making, followed by a reflection on the research limitations found during the research process. Finally, further suggestions and recommendations are provided for future RURB policymaking and research directions.

2. Literature Review

2.1. Introduction

This chapter aims to deliver the first research objective: to provide a comprehensive literature review to explore the problems and research gap in the current knowledge of RURB policymaking, academic studies, and engineering practices in China; and to learn the required knowledge in the field; and to find the insight for this research based on previous experience.

Reviewing, studying and thinking of the relevant literature is one of the mandatory approaches to reviewing the past and preparing for future academic research (Webster and Watson, 2002). The literature review is the mandatory section of all academic research which provides the fundamental references to learn and absorb the knowledge of the field. It can also discover the research gap, innovation, methodology applications, and predicted research contribution. To have a deep understanding of the building retrofitting research, as well as a clear picture of the relevant knowledge, it is mandatory to comprehensively review and critically analyse the national building policy, published papers of academic studies, and reports and books on building retrofit projects.

In this chapter, a comprehensive literature with three flows of the historical development of RURB policy in China, the current literature of published research, and completed RURB engineer projects, are presented to acquire the relevant current knowledge of RURB. The evidence of critiques and insights of both current circumstances and problems are hence obtained to support the design of research methodology from RURB policy, studies, and projects.

2.2. Review of current building energy policy in China

This section reviews the current literature on RURB policy content and archives issued by the central government to acquire knowledge of the policy development of residential buildings, building retrofit, and energy conservation in China, the case study country. More specifically, the same author of this study, the developer of this research (Han et al., 2021) had presented a comprehensive review research of the whole development of energy conservation policy in China over the last 40 years, and the building retrofit has been criticised as one of the most serious weaknesses of current building policy development.

2.2.1. The development history of building energy efficient standards (BEES)

In building energy sector, the top-down administrative policy has been discussed by Li and Shui (2015), Wu et al. (2017) and Gacitua et al. (2018) to be the most powerful tool to achieve energy-saving targets, with the strong executive ability provided by government and laws argued by Potůček (2018). Energy policy for new buildings and building retrofit in China can be specifically defined as Building Energy Efficient Standards (BEES), similar to the concept of 'building regulations' used in European and American countries. In China, RURB policy and standards are very dependent on new building standards - which state the design principles and rules of building parameters and performance index (Han et al., 2021). The development history and milestones are reviewed using content and chronological analysis, as shown in Figure 2.1.

As argued in the introduction chapter, the unclear reality is an important difficulty due to the diverse conditions of residential buildings. China has a very large territorial area, almost all kinds of climate and landform conditions, and diverse occupant's economic levels, thermal adaption, and cultural habits. Therefore, challenges were early found when people attempted to set an extensive, general building standard for the whole national use.

Overall, the BEES for civil residential buildings were divided into specific three climate-respond standards based on the climate zones, such as BEES for Severe Cold and Cold (SC & C) climate zones (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 1996) in 1987; in 2001 for Hot Summer and Cold Winter (HSCW) climate zone; and in 2003 for Hot Summer and Warm Winter (HSWW) zone. In 2000, the Chinese 10^{th} Five Year Plan (FYP) was the first time stating energy conservation retrofitting for buildings as one of the national objectives (National Development and Reform Commission, 2001). Following the 'transition of national development strategies' stage, the priority of sustainability was raised above energy and economy development. As Han et al. (2021) stated, the first policy considering climate-respond techniques in building energy conservation was the JGJ 134-2001 standard, which could be the 'milestone' of residential BEES development.

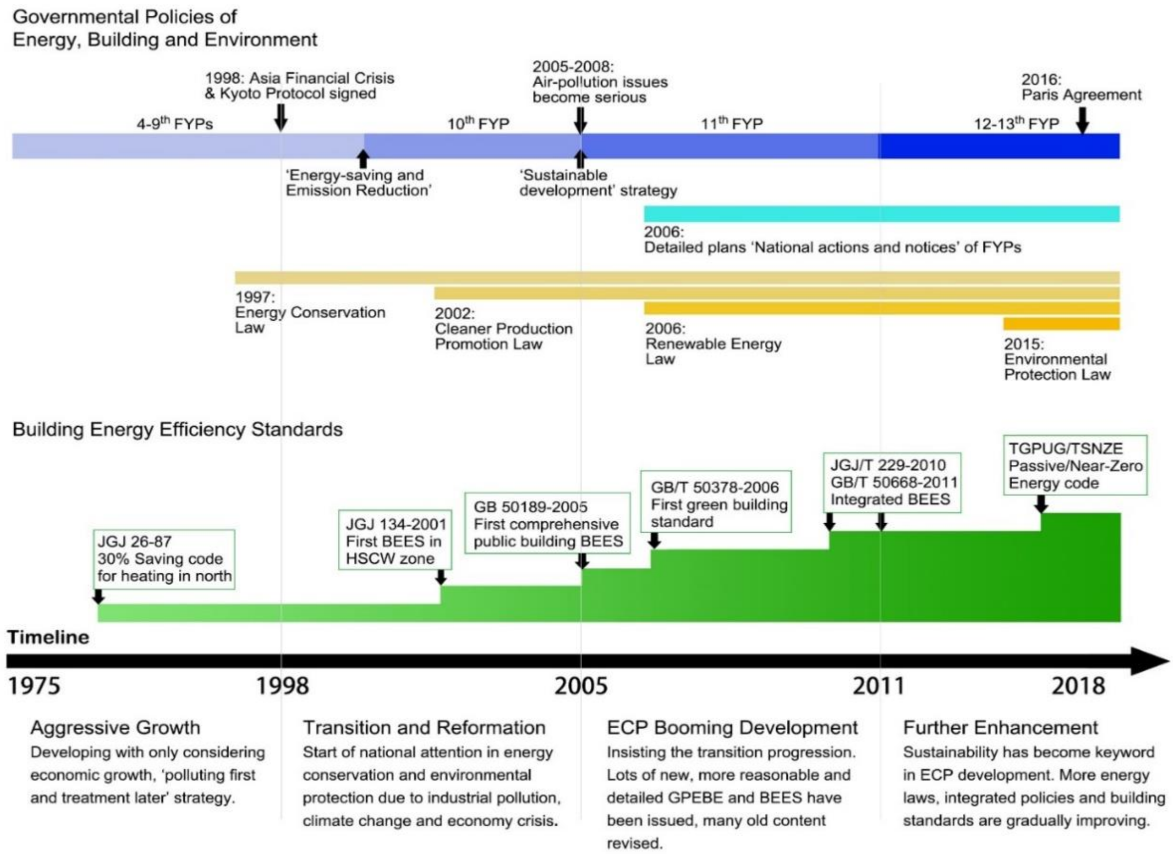


Figure 2.1: Development history and milestones of building energy policy in China. Han et al. (2021)

For residential buildings located in northern China, JGJ 26-2010 (1995, 1987): The design standard for energy efficiency of residential buildings in severe cold and cold zones, was the milestone of BEES development in 1987, and a 30% energy conservation rate was set compared with 1980s buildings. The traditional district central heating system (with a centralised heating station to support a very large building area, burning coals) is widely used in these climate zones, which causes a serious problem of air pollution particles and carbon emissions. Therefore, improving the efficiency of boilers and the system of heating stations was the biggest consideration in 1987 and 1995 (energy conservation rate improved to 50%) version of this standard (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2010a). Starting in 2010, as the designed energy conservation rate was further increased to 65% (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2010a), there was more attention paid to the passive design index of building thermal performance, including minimum building envelope U-value and air-infiltration, but not enough on the view of nowadays. Then, this standard has not received any updates for 8 years, and many design parameters were no longer reasonable and become obsolete. As the version of JGJ 26 was delayed until 2018 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2018), there was a large stock of residential buildings have become 'old residences' within 23 years, which showed the negative result of the low frequency of BEES updates.

The BEES of southern China were further divided into HSCW and HSWW standards. JGJ 134-2001: Design standard for energy efficiency of residential buildings in hot summer and cold winter zone, deal with the climate zone which has much more complicate weather conditions – the summer is longer and extremely hot which can reach more than 40 °C; the winter is shorter with average air temperature around 5 °C and very humid. Therefore, although the winter in HSWC is not that severe compared with in SC and C zones, indoor heating devices are still required to reach the basic thermal comfort environment (no district heating system for this climate zone).

Yet residents living in the HSCW zone did not use any artificial heating in winter for a long time because of the low economy level. They just endure and suffer from the cold temperature despite the uncomfortable thermal feelings (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2001). As a result, the BEES of HSCW zones issued in 2001 focused more on cooling equipment efficiency, shading, and natural ventilation to deal with the extremely hot summer. In the newest version of JGJ 134-2010, the minimum requirements of building envelope such as U-value and infiltration level have also been much improved (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2010b), but the problem of large old building stock caused by 9 years no-update was also serious similar with the situation in SC & C zones.

Similarly but with even less content, JGJ 75-2012 (2003): Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Warm Winter Zone, was usually released after two years of JGJ134, which could be seen as a special version of JGJ134 with less content of heating, but a little bit more approaches to solving problems of high temperature in summer (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2013), such as energy conservation techniques in indoor air-conditioning. Considering overheating issues, JGJ75 has very flexible rules in building envelope designs, but many unique mandatory demands in shading, dehumidification and ventilation, which are reasonable based on the weather condition this standard applies (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2012b), but same as others, this standard has not been upgraded for 6 years. Due to the mild climate in winter, this climate zone has fewer requirements in building retrofit of energy-saving aspects compared to the SC, C and HSCW zones.

2.2.2. Building energy policies related to the RURB

According to Liu et al. (2020), gradually increased top-down administrated building policies were developed by the government which attempted to push the speed of energy saving in residential buildings. Yet the reviewed BEES named 'JGJ' are all BEES designed for new residential buildings. As Han et al. (2021) argued, the BEES for building retrofit has much less policy content and governmental attention. Energy saving objectives in the RURB sector were on a less important stage in the ultimate national development plan for a long time, as in the Five-Year-Plans (FYPs). Either the policies of retrofit were standards with the least content and fewer mandatory design rules than other new building policies. Until today, the RURB policy and BEES are still considerably weak for their very brief content, lack of supervision strength and engineering guidance (Han et al., 2021).

From the view of policymakers, the report from the China Association of Building Energy Efficiency (2016) representatively proved the effects of BEES applications are magnificent from 2007 to 2014 – there was a 10% annual energy reduction rate in urban public buildings, but only 5% in urban residential buildings. Meanwhile, going over the issued policy relevant to RURB, Han et al. (2021) found that the national rules and objectives set for building energy efficiency retrofit are lower than new buildings, and the content in existing building standards is much less than other new building standards.

Historically, the beginning of building policy for RURB in China was the standard JGJ/T 129-2012: Technical Specification for Energy Efficiency Retrofit of Existing Residential Buildings. It is a very general standard for energy efficiency retrofit, without frequent upgrades, but many of its index and evaluation method is based on current residential new building standards. For example, it simply asks to retrofit designers to improve the insulation for a 5% to 10% increased U-value of the building façade compared to the new building standard (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2012c). However, there is no explanation of which retrofit measures, techniques, and materials are suggested or required to be used during the retrofit design. This means that building retrofit policies have less content compared with new building standards, and the lack of engineering approaches for retrofit could be a problem of effective implementation (Kelly, 2009).

The language used in retrofit policy is more cautious compared to the BEES of new buildings and public buildings. Currently, the newest BEES for RURB was issued in 2022 named GB 55022-2021: General Standard for Maintenance and Renovation of Existing Buildings (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2022b). Similar to the previous building retrofit standards of JGJ/T 425-2017 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2017b) and JGJ/T 129-2012 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2012c), this standard still does not have 'mandatory' rules and index for building façade and retrofit techniques for old residences, but only provides some "suggested" engineering approaches for RURB.

This uncertainty shows that even the RURB policymakers have no confidence in suitable retrofit techniques during the design of retrofit standards. Fortunately, as an improvement, this standard has stated the official questionnaire design for communication with the residents who live in old residences. As a result, there is a remote but urgent path for the country to claim the energy-saving and emission reduction potential in building energy retrofit.

2.2.3. RURB policy: on the views of academic researchers

Scholars have argued that statistics of annual energy consumption from residential buildings have also shown an important message: urban residents have significantly increasing requirements for better indoor thermal comfort as the national economy is fast improving (Xu et al., 2013, Lin et al., 2016). This phenomenon has shown a conflict between energy conservation and better living comfort. It is unavoidable that residents who live in old residences may spontaneously introduce more and more indoor heating, cooling and other electronic devices, and increase the usage of HVAC equipment to increase thermal comfort. From the view of RURB policymakers, they must consider and control energy consumption to achieve the national objectives of energy conservation and carbon emission reduction. Therefore, it is the most sustainable approach to have the old residential buildings retrofitted with better building thermal performance and energy conservation measures.

Furthermore, from the view of retrofit designers and engineers, the conventional approaches to building retrofit such as in the IEA retrofit programme (Alexander et al., 2017), designing retrofit scenarios is 'setting a target and casually filling the models with techniques', rather than strictly following the RURB design standards as new buildings. This project-based thinking relies on personal professional experiences – empiricism engineering. Accordingly, it is found that different professionals may have very diverse opinions when proceeding with the modern development of the RURB career. It could be the main reason that the current RURB progress is inefficient. It can no longer satisfy the requirement of RURB progress, which needs much more accurate and realistic data to evident and motivate residents.

Furthermore, residents, as an inhabitant, should be a very important role in RURB, but it is criticised that they are usually ignored by the majority of professionals during the RURB policymaking and design due to the difficulty of collecting opinions from massive and diverse residents (Han et al., 2021). However, residents are the final decision-makers who can veto all the works made by professionals. It could bring a waste of time and effort for professionals to set policies and make retrofit designs themselves and get refused by residents due to the lack of communication. Therefore, it is necessary to unite all the retrofit demands, objectives, and thoughts from both professionals and residents to have more scientific and effective RURB policymaking and design.

2.2.4. Discussion and critiques of RURB Policies

The two critiques argued from the RURB policies can be summarised below:

Less attention: Based on the statement by Han et al. (2021) in their historical development review of the building energy policy in China, **building retrofit** attracted a very small proportion of national attention compared to the new building policy from 1980 to 2020. Moreover, the building retrofit policy gave little attention to the

residential building retrofit sector (compared to public and industrial buildings) and even less attention was given to the **retrofit of urban residential buildings** (compared to rural residential buildings). Under this circumstance, the RURB had the lowest priority in the currently implemented building energy policy and BEES in China, with the least policy content and lowest frequency of policy updates. Therefore, this low level of attention from the national government caused the limitations of related policy reliability, design, executive ability, manpower and available governmental budget. Hence it could be argued to be the main reason hindering the speed of development for RURB.

Low reliability: The language used between BEES of new buildings and building retrofit brings a significant difference in policy reliability. Based on the reviewed BEES content, new building standards have very strong statements indexing the requirements and performance of building façades, designs, and engineering measures, as the mandatory rules. Hence these standards are very reliable for building designers and engineers while selecting construction techniques, building materials and indoor devices.

However, for building retrofit standards, the language used involves suggested recommendations. For example, the statement from retrofit BEES is 'old residences should be introduced with insulation on the external walls', without explanation of materials, U-values, and engineering measures. As a result, the current retrofit BEES is very difficult to use and execute. RURB designers must explore the reasonable selection of retrofit measures from other resources such as project reports and others' experiences.

Accordingly, the insights learned from the current literature on RURB policy aim to increase the governmental interest and investment in the national policy of the Five-Year Plans. The related ministry offices can therefore design more reliable and effective building retrofit standards with clear statements and requirements for the design index for RURB designers and engineers. Emphasis should be given to reasonable mandatory rules for retrofit designs, including the selection of retrofit measures for energy conservation and a normalised retrofit index to improve the old built environments.

Meanwhile, lessons have been learned that the authority of RURB professionals is reduced since residents may still refuse to cooperate even though the RURB works bring many benefits. In this case, humanistic thinking should be used to improve the ability to execute the RURB policy. RURB policymakers should consider residents as important involved participants, rather than isolated and passive receivers. The communication process between RURB designers and residents should be programmed by RURB policymakers as official paperwork to increase communication efficiency.

2.3. Review of current RURB literature of published studies

This section presents the review of current published research related to the RURB, classified based on the research methods and data resource types.

2.3.1. Policy implementations

Historically, the top-down administrative building policy in China has proven that the effectiveness of energy conservation promoted by building policy has been very appreciable in China. For example, Peng and Liu (2016) and Huo et al. (2018) used a top-down calculation method based on national statistics, estimating a high 17.7% to 20.3% energy conservation effectiveness in the building sector due to building energy policy implementation. Jiao and Boons (2017) used both statistic calculation and case study methods to translate the circular economy policies and showed their results in energy conservation.

Furthermore, Chai and Zhang (2010) provided different scenarios of ECP transitions in the 10^{th} Five Year Plan (FYP) and made projections of their effectiveness till 2050, showing a 25% CO_2 reduction in 2020 and an over 50% rate of renewable energy usage could be reached in 2050. Research from Yuan and Zuo (2011) and Tan et al. (2018) have presented a review of both policy clauses and statistics, they acquired the reduction and 2050 projection data of carbon emission effectiveness, while Tan et al. (2018) simulated and admired the progression of current ECP which can reach the objective of 50% CO_2 reduction in 2046, 4 years before the 2050's target. These remarkable achievements have shown the importance of the top-down administrated building policy in energy conservation and sustainability improvement, and it could be trusted that building policy can be one of the strongest forces for building retrofitting development.

2.3.2. Statistical studies for the retrofit purpose

An extreme side is the studies using governmental statistics as their primary data source, as top-down building stock studies. They present the building site energy consumption data and carbon emission situation using a large-scale database from national statistics. This kind of study fully relies on the data provided by others, rather than the researchers themselves. The data provider must be checked as a trustful resource, while only country government-based data should be used for the analysis rather than social media or company surveys.

Generally speaking, for China building stock studies, the major resource could be found from the National Bureau of Statistics of China, and more professional data from the Ministry of Housing and Urban-Rural Development of the People's Republic of China (2017a). Similarly, in the United Kingdom, National Audit Office (2017) provides the housing report in England, and the Department for Communities and Local Government (DCLG) (Hamilton et al., 2013) for the London housing survey, as well as the document (Ministry of Housing Communities and Local Government of the UK, 2018), provides the latest UK stock data of annual build dwellings report, but its annual report does not have a total building stock statistic data for the entire country.

Compared with realistic survey data, there is some prediction research for building stock analysis, based on statistics and the average building life cycle features. For example, in China, Tsinghua University Building Energy Research Center (2013) provides an annual report on energy building efficiency every year constantly based on building stock modelling and calculations. However, this kind of country-size data sometimes is too general for researchers and policymakers to evaluate.

On the other hand, Baynes and Wiedmann (2012) concluded general approaches for assessing urban built environments and stated that the 'traditional' single building simulation studies are also not able to satisfy the increased detail data quality requirement of building stock analysis of built environments, which means an approach of detail building stock and energy analysis with large scales and districts such as urban to transnational scales have become necessary due to their features of more building complexities and higher data quality.

For urban-to-transnational scales analysis, Pacheco-Torres et al. (2016) presented a way of an order-reduced model to reduce the complexity by using less set of building parameters, but this simplification could lead to the result not being trustful. Elci et al. (2018) have reviewed and concluded some new strategies, one is representing several buildings with one building model, the second is using archetypes-based reference buildings, and the third is developing building prototypes to represent statistical averages for actual buildings.

Top-down statistic-based studies are also able to show future projections such as in building energy, population, building amount, and material used for retrofitting. Hong et al. (2016) have presented a study which projected China's building stock amount from 2015 to 2050. This research uses the bottom-up turnover model to calculate the dynamic future building stocks, and the building material consumption and building retrofit trend is assumed. The study shows a generally decreasing trend of new construction amount with a smooth increase in residential buildings.

The modelling method of floor area projection could also be a concern because the average building lifetime factors from Song (2010) are applied in the equation and the commercial building stock projection is induced by using unemployment rate and GDP factors from McNeil (2012). These social factors quoted are not obtained from very official data sources, and they may have significant gaps with different regions, climate conditions, urban or rural areas, populations and even economy level and culture features. Besides, this 2015 to 2050 projection of building stock has ignored all the policy influence, which means the result in the whole country view may not be realistic enough. However, studies such as Hong et al. (2016) can only provide estimated short-period building stock projections without quantitative simulation. Therefore, for statistic-based studies, their strategy could lead to a trustful trend for regions using distinctive factors, but it is difficult to be used for the decision-making for the RURB.

2.3.3. RURB studies with the scale of Building-by-building

The current studies that use large-scale thinking as urban building stock to analyse the energy or population changes can be identified as having two extreme sides. One is the bottom-up single building-by-building method, and another is the top-down statistical method. In this section, some representative studies with these two methods are reviewed to find the research gap of current solutions to the RURB system.

Not only engineering works of building retrofit are always designed and finished by the single building-by-building approach, but the retrofit studies also used the bottom-up method is similar to one building model of the IEA EBC Programme. Even at the building stock level, Mastrucci et al. (2017) define a building-by-building approach for building typology aggregation, which models building one-by-one for the entire stock. The total performance data of the research area are obtained by summing-up all individual buildings. This strategy could improve the accuracy of the modelling process, but the detail data of the stock are not always available - so it is required to assume the not obtainable parameters, as stated by Saner et al. (2014). Also, it is very time-consuming if the scale is large with too many buildings. Consequently, bottom-up building stock analysis using detail archetypal aggregation or using spatial building models related to geographic information systems (GIS) seems to be the better approach for building stock aggregation and energy analysis.

2.3.4. RURB modelling with archetype aggregation

Since the single building scale studies cannot satisfy the RURB, it is necessary to review the studies' focus on 'a group of buildings' as their research objects. Mastrucci et al. (2014) have reviewed much relevant literature and highlighted the stock aggregation approaches as the 'archetypes approach', 'building-by-building approach' and 'GIS integration'. They stated that the archetype approach has been widely adopted and broadly used to represent entire building stock by classifying buildings with age, size, house type and functions (as prototype buildings), which can minimise the complexity of the study, but the over-simplification risk is considered high.

For large scales like national, the number of prototypes needed will be fast increased. For example, Famuyibo et al. (2013) analysed the Irish nation-building stock using 13 archetypes but only covered 65% of the residential buildings – as the strategy of archetype aggregation requires plenty of assumption, the accuracy of simple archetype aggregation may only allow this approach for small scale stock studies such as neighbourhood scale. However, there are a few studies that presented considerably successful practices, as Mata et al. (2014) studied the archetypal aggregation approach for building stock analysis in France, Germany, Spain and the UK, with a large number of 99, 122, 120 and 252 archetypes for each investigated country, and combined them with the statistical data resources of building numbers. They compared the simulation result with the realistic statistic data and stated that only a -

6% to +2% difference was acquired, and the conclusion could be defined as satisfactory. Although it might be considered as reverse reasoning and explaining for the EU national stock statistic due to this study using plenty of other people and organizations' resources, it still means archetypal description strategy could do part of the important job for the building stock analysis if the segmentation categories are detail mentioned during the aggregation process.

2.3.5. Geometric approaches

Referring to a more detailed physical model resource, Mastrucci et al. (2014) and Jakob et al. (2013) started to consider spatial modelling to assess building energy use data, on an urban scale with a GIS dataset. This strategy of modelling could efficiently estimate the energy consumption situation in urban residential zones when the geographic information of buildings becomes easier to obtain and apply in the energy simulation systems. Similarly, Elci et al. (2018) presented a thermal building simulation using a GIS aggregation approach in a small urban district scale with 35 individual buildings. They used the site plan to map the buildings, with their building parameters defined using an archetype classification strategy to simulate and evaluate the thermal performance. Although the thermal analysis is not strong enough due to the lack of thermal factors detail mentioned in this study, it could be a new hybrid approach to building stock analysis using both archetypes aggregation and GIS integration.

For building stock, Buffat et al. (2017) have developed this technical approach for building stock modelling and energy implementation illustration, which used spatial and digital evaluation GIS datasets for the modelling method, as building footprints were applied to identify buildings. It is believed that this GIS building modelling approach could significantly improve the accuracy when calculating or simulating the building energy-related data in multiple building zone studies, such as in urban-level stock analysis. Their research also considered specific city building dimensions, physical properties, climate data and user behaviour, however, the total building footprint simplification might be too general during the modelling due to buildings being converged as simple building shapes. It leads thinking for future similar research when doing multiple building zone energy analysis and better with a high-quality GIS building information database. Previously before 3D modelling become available, Österbring et al. (2016) and Nageler et al. (2017) studied building stock with scale as city and town zone levels were using a 2.5D vector dataset during the modelling process, their model establishment are more complicated and time-consuming compared with the GIS model data generator provided by relevant mapping company.

2.3.6. Clustering method based on building performance

For buildings located in different places, stock aggregation with large scales not only need to consider building archetypes, but also multiple building features such as climate condition, population density, nature resources, culture, and racial traditions, which may significantly affect energy usage. For example, Csoknyai et al. (2016) have studied the building stock characteristics and energy performance from residential buildings of Eastern-European countries, and the differences are significant although the climate is mainly continental, stated that the historical influence is one of the most important aspects.

Moreover, Vásquez et al. (2016) present a comprehensive dynamic type-cohort-time modelling which was driven by the building performance, to provide the trend of building stock increase and demand of energy consumption from 1800 to 2100. In this study, plenty of aspects of demographic, lifestyle, building characteristics, renovation cycles and policies are taken into consideration during the modelling process, and Germany and the Czech Republic (climate condition that requires winter heating) are selected as different case studies with 4 scenarios. It is worth noting that individual energy and greenhouse gas reduction policies of the two countries are also considered and applied during the modelling, which made the result more trustful. However, there are some uncertainties in this study such as its theoretical delivered energy calculated does not cover the indoor plug-in energy, and occupancy rate condition in buildings is not considered. Therefore, the rooms that are not heated and air-conditioned are also involved in modelling, which causes the total energy demand is usually higher than the real statistics.

With even more complex factors, Schwede and Lu (2017) provide metabolic evidence of an entire national economy related to country size, national composition and other complex dynamics. Likewise, Delmastro et al. (2016) successfully provide a socio-economic model and analysed the energy conservation potential of the whole building stock, by using the GIS method. More relevantly, Li et al. (2018b) provide a much more detailed approach to cluster satellite models into six different reference building types, within a particular urban zone. These studies mapped the distribution and flow movement condition of built ages, resident movements, economy changes, or anthropogenic material movements. They have provided successful practices to analyse the complicated dynamic information of building conditions and performance, while the potential of energy or materials saving is defined as the 'metabolic rate', to making suggestions for policymaking. Therefore, the GIS-based survey models can be used as an improved method for urban scale analysis.

2.3.7. Urban-scale RURB studies

As argued, expanding the scale of RURB research should be the solution to deal with the low-efficiency issue in a single building-by-building approach. Dixon and Eames (2013), Eames et al. (2013) could be the beginning of modern urban-scale retrofitting studies. Their research explored the cities' future by applying and transiting sustainability through urban retrofit. The two studies raise the single building approach to a higher level as a city scale and attempt to explore the research challenges of large-scale building retrofit, including historical data and trends, policies or government legislation related to the building retrofit, the current state of scientific understanding, key technological advances of renovations, change issues and critical uncertainties, and a long-term future vision of the cities. Furthermore, the literature from Dixon et al. (2014) and Ferrante and Semprini (2011) maps and shows how sustainability techniques, city planning and architectural designs could work together for even longer-term retrofit achievements such as a 50-year future for the cities.

It is similarly proven by more recent published papers, as a study from Hargreaves et al. (2017) shows that RURB studies could provide useful data for forecasting future energy and carbon emission based on the simulated settings of RURB levels. Moghadam and Lombardi (2019b) also used a multicriteria spatial decision support system for energy retrofitting of building stocks, which may change the traditional thinking in urban energy planning. Accordingly, these studies all provide plenty of useful thinking, potential benefits, and challenges of scaling up the building retrofit from a single building to a city level.

More specifically, urban energy simulation is raised as a research method that combines building energy simulation and urban-scale thinking. In the RURB case, the traditional simulation approach of simulating building retrofit effects individually for each building model and scenario could not be a satisfactory method. Single-building model simulation is not effective to be edited and is very time-consuming when the scale is up to the urban level, as mentioned in the limitation section of the research (Han, 2015). Furthermore, as urban building stock and retrofitting are typically 'dynamic' due to the time consumed by the evaluating, construction and engineering work, the dynamic simulation could be a better approach to present the improvements in energy, living quality and thermal comfort of RURB, similar as some studies which apply modelling for the analysis of new construction and demolished buildings.

Müller (2006) has discussed the physical material accounting using a generic dynamic material flow model in the Netherlands 1900-2100, which was a new method for estimations of building stock information, works for analysis of population growth, building style changes, building material demand, and waste generation. Hu et al. (2010) have analysed the input and output flow relevant to building stocks. In this study, the target is limit selected as only one typical city, and the building function is only residential. Also, the input data of transformation, accumulation, and the building material output situation from 1949 to 2008 was discussed. Their analysis presented the ecological and economic impact of China's rapid urbanization in modern cities and provided a good practice in building stock studies because the specific policy, historical and cultural characteristics could be appropriately applied to make the suggestions and future projections more reasonable and useful. These results could provide successful and exciting proofs for the future use outcomes of RURB analysis of this research. But on the other hand, the policy suggestion made by Hu et al. (2010) is not easy for general use such as at the province level due to the systemic approach was not well structured. It shows that for large-scale cases, the results become much more complicated if there are more detailed local factors involved.

The simulation result analysis with large-scale stock data could also present the changes in energy consumption, and material usage between different built ages, which could be good examples for the RURB analysis in this study. Take material flow as an example, Cao et al. (2017) studied the in-use cement stock research in China from 1920-2013 using top-down dynamic material flow analysis as Kapur et al. (2008) did for the United States. Cao's research found a sharp increase in the in-use cement stock in modern China and stated this cement stock is now still at a young age, which reflects that there was a remarkable improvement in newly constructed dwellings after 1990.

Combine this study with the work from Pauliuk et al. (2011) which studies the steel cycle in the Chinese building stock, a clear result can be found that building stock built in the years between 1990-2010 had a significant difference in material usage compared to buildings built in 1950 to 1990, as steel based building was gradually replacing the timber material and cement base buildings. This phenomenon is very important for the building stock analysis since it shows the building lifecycle is a dynamically increased factor for new buildings with modern improved materials – similar to the increased demand for living quality is causing a rapidly increased demand for retrofitting. Also, their difference in building performance could lead to a more complicated situation for further use, such as energy and material demand/waste analysis. Accordingly, the modelling results provided by the RURB simulation could be able to present the effects of dynamic urban energy, material flow by retrofit, carbon emission changes, or other data changes based on the retrofit scenarios set.

2.3.8. Discussion and critiques of current RURB studies

From the arguments of the literature reviewed above, current RURB studies are criticised for their problems in research scale, modelling, the conflict between retrofit benefits and a lack of consideration of residents' needs:

Single building scale: the current literature of building retrofit modelling and simulation studies share a common issue: their scale may usually be the single building or one building type. The majority of studies presented the building retrofit results based on single-building modelling and simulation processes. It is arguable whether the reliability of the retrofit results of single-building-scale research allows them to be promoted to the urban stock level using the bottom-up method. From the practices of Mastrucci *et al.* (2017) and Saner *et al.* (2014), the single-building scale was proven to be one of the research limitations while too many assumptions must be made. Since the RURB policy will be implemented in a large region, city or country, the results provided by single-building-scale RURB research are not useful as evidence for policymaking on an urban scale. Therefore, the geometric approaches or building clustering methods may be more productive for urban-scale RURB analysis.

Oversimplification: The risk of oversimplification is another serious problem during RURB modelling. The majority of related studies use only one building model to represent all the urban building types during modelling and simulation, as Baynes and Wiedmann (2012) stated. Meanwhile, the majority of building simulation studies chose to use only the building information provided by the national building standards or documents, rather than realistic conditions. Therefore, data accuracy between the building models and the real buildings is a big concern. Moreover, the target retrofit effects of the building models are set before the retrofit or simulation, usually a percentage of energy consumption reduction, but the details of the retrofit design are not fully explained and justified with a clear boundary. For example, many building simulation studies stated a conclusion on the total energy saving percentage through retrofit packages, but some of the researchers did not clarify the analysed energy source type (such as coal, electricity and/or natural gas), how they confirm the occupancy behaviour profiles, the reasons for selecting the retrofit measures and how they designed constant settings (with clear references) during the simulation.

Conflict: Scholars have argued that statistics have also shown an important message that urban residents have significantly increasing demands for more comfortable built environments (Xu et al., 2013, Lin et al., 2016). Residents prefer to introduce more heating and cooling devices and increase their usage to acquire better thermal comfort in old residences. This trend has raised a conflict between energy conservation and comfortable living conditions. For example, residents may install more air conditioners, heating devices, fans, lifts, smoke detectors and more lighting bulbs in old residences to improve their living environments – which will significantly increase the total energy consumption. In this case, scholars should balance these two factors – although reducing energy use is important, it is not acceptable to sacrifice the comfort level of the indoor environment since improving living quality is also the core purpose of RURB in the view of residents.

Isolation: It is found that current studies of RURB professionals and residents are usually separated and isolated. Research with RURB energy, cost and comfort purposes considers RURB professionals (policymakers, engineers and researchers) as the only people involved. In this case, the diverse opinions, persistence or impediments from the building owners and residents will be neglected during the retrofit design. Research with RURB occupancy behaviours and control systems considers ‘residents’ as the only people involved. In this case, the suggestions provided by RURB professionals will be treated as interference during the observation and questioning of residents. However, both cases are too ideal to be realistic situations. For example, although the RURB professionals may have designed a wonderful retrofit plan, residents may still refuse it due to their personal preferences. On the other hand, the guidance proposed by RURB professionals has been proven useful in reducing the energy wasted in residential buildings, such as lighting and shading control.

The review of RURB studies provides insights for this research by showing that the current research methods can satisfy the objectives of the RURB study, but only with scientific selection and a combination of the appropriate approaches. Initially, compared to the traditional single-building scale, scaling up the building retrofit studies to a large urban scale could yield more visible and useful data for future cities. The urban-scale RURB studies can provide more reliable bottom-up stock data for city planners and policymakers to design a normalised retrofit policy suitable for use for a whole city. However, oversimplification is found as the key problem in urban-scale building research, hence the reliability of urban building modelling, whilst difficult, must be guaranteed. Therefore, the selection, adaptation and relevance of research methods used in the current literature should be considered, such as field surveys, GIS and building typology methods.

Meanwhile, the conflict between reducing energy consumption and improving comfort and the environment brings an important research principle for RURB: the RURB design and process must not sacrifice or hinder the improvements in comfort, safety, functionality, and environment. The issues of energy and carbon saving should be solved in other ways including passive energy conservation techniques (to increase the thermal performance of the building façade), renewable energy sources (to reduce carbon emissions) and control systems (to reduce energy waste) (Cao et al., 2021). Finally, the isolation between RURB professionals and residents should be broken. Social issues related to residents should be treated as unavoidable influencing factors during RURB research. The individual opinions, demands and preferences of the resident should not be isolated during the RURB analysis but treated equally with those of participant groups like RURB policymakers, designers, engineers and scholars. Similarly, the knowledge from RURB professionals should become useful resources to reduce energy waste by guiding the residents' behaviours and applying control systems for indoor energy-related devices.

2.4. Review of RURB projects and case studies

2.4.1. National RURB engineering practices in China

Generally scanned the literature related to building retrofit in China, it is interesting that almost all the retrofit project reports have at least one case study building with 'before and after' result analysis to evaluate their retrofit effects. When going deeper, it is found that they choose their renovation techniques based on their objective settings. On the other side, when the objectives have been achieved, this process of introducing retrofit techniques will be terminated immediately to avoid further costs. In this case, retrofit designers and engineers may not take more technical applications to achieve even better results of sustainability.

Meanwhile, the engineering experiences of sophisticated retrofit designers and engineers take the most important role when choosing retrofit techniques. It means that the selection of retrofit measures in the majority of RURB projects was very empiricism. It could be understood that there is currently no very reliable, developed, and comprehensive retrofit theory or widely recognised retrofit standard available as a reference.

This 'accumulation of experiences' phenomenon was found more convincing when reviewing the development of China's retrofit research: the Yearbooks of Existing Building Renovation in China (China Academy of Building Research, 2010, China Academy of Building Research, 2014, China Academy of Building Research, 2016, China Academy of Building Research, 2018). This book series is published by the China Academy of Building Research, which could be the most authoritative and comprehensive literature on China's building retrofit. They contain many case study projects of building retrofitting every year. In these books, all the relevant elements are included in the development of building retrofit policy, building standards, technical research, analysis of retrofit achievements, published papers, and demonstration projects.

As this book series is keeping updating each year with plenty of new studies, projects and thinking, the information and practices provided are valuable for scholars who want to further develop the building retrofit career in China. However, the empiricism problem that exists in this book series is easily discovered. Firstly, these project reports have no explanation of why the retrofit designers chose the applied retrofit techniques. Secondly, the majority of the retrofit results analysis provided only considered energy and functionality improvement, which the economic cost, engineering difficulties, design process and social issues are neglected. Thirdly, most project reports have not mentioned the communication process with the affected residents. In this case, it shows that the current building retrofit projects in China still rely on the experiences of retrofit designers and engineers, as the accumulation of projects. There are no developed and systematic theories, policies, or reliable design standards for RURB projects.

2.4.2. International RURB projects

An international research-based project, the International Energy Agency Energy in Buildings and Communities Programme (IEA EBC Programme), has been reviewed as it has provided excellent knowledge of building retrofitting studies and case study practices among its subtask, as IEA Annex 46, 61 and 75. While other projects of this programme are energy-efficient techniques related to research, the deep retrofitting and renovation projects identified new integrated strategic areas in which collaborative efforts may be beneficial for at least a 50% energy conservation rate and relevant carbon emission reduction in existing buildings (International Energy Agency, 2017). Therefore, although the Annex 46 and 61 projects focus more on office buildings and public building retrofitting, they are still valuable to provide insight into RURB knowledge and practices.

For an integrated approach to building retrofitting, the Annex 61 project provided a book on Deep Energy Retrofit (Alexander et al., 2017), which is chosen as one of the core literature for this study due to the comprehensive information, case studies and research conducted related with the energy retrofitting. This research-based project could be seen as the most comprehensive, representative, and newest in the retrofit field. This 522-page document showed how could the strongest force of built environment researchers cooperate internationally, using the most advanced techniques of every element in the building to achieve the objectives of energy conservation and sustainability by applying retrofit. Annex 61 project report also developed the retrofit thinking: “bundles of techniques”, as it is the core integrated approach to apply multiple technologies simultaneously to achieve higher efficiency for the retrofit results.

Yet there are also some drawbacks within the retrofitting projects of the IEA EBC Programme. One of the biggest concerns is the scale of research. In Annex 61 deep energy retrofit for office building projects (Yao et al., 2016), although there are many retrofit scenarios and the simulation has considered all five climate zones in China, the building model is still using one simplified building model. Similar to many other retrofitting studies, the scale has limited its application in uses such as communities or zones in the urban area, so it can only be used for single-building retrofitting engineering, but not suitable for a more general evaluation use for the government and city planners. For RURB studies, since residential buildings have many more unique features in building shape, the built environment and occupant behaviours, this can be amplified into a great issue as the results from the single-building model are no longer representative.

Another concern from this literature is that these retrofitting projects strictly followed the definition of deep energy retrofit described by the project team of Zhivov et al. (2015) for a 50% energy reduction goal compared with the baseline. Regardless of wondering if ‘50%’ is suitable for all the countries involved in the project, this fixed value caused the retrofitting scenarios settings to become unreasonable if the baseline models are variable for too high or too low in energy use intensity. For example, if the weather condition in the selected research building is very extreme, the simple heavy-retrofit of thermal insulation could easily lead to a 50% energy reduction for heating or cooling, so the other techniques may be no longer needed (Yao et al., 2016). In this case, the bundles of integrated techniques which are applied in the building model are too dependent under this 50% index, so it may not be very efficient for common use for other types of buildings.

As Alexander et al. (2017) stated, public buildings only involve building owners as executive decision-makers and energy managers during building renovation, but residential building research, however, has to consider much more about the individual residents which causes more challenges with social issues. As a result, on a large urban scale, both 1) how to design a retrofit plan to satisfy residents with different retrofit demands and budget, and 2) how to persuade residents to make retrofit decisions, could be two complicated difficulties due to their complex nature of local social, technical, economic, and cultural characteristics.

2.4.3. Discussion and critiques of RURB projects

Accordingly, the current literature on completed RURB projects provides valuable engineering experiences, but they are also challenged with the problems of empiricism, low efficiency, and resident coordination:

Empiricism: From the RURB project reports reviewed, the majority of building retrofit research reviewed consists of engineering experience-based quantitative studies. Due to the lack of reliable design standards, both the selections of retrofit measures and materials require personal experiences from retrofit designers and engineers, which can be critiqued for their flexibility and uncertainty. For example, different retrofit designers may have completely different preferences for building insulation types when retrofitting the external building façade. In the view of researchers, current RURB projects do not have academic explanations and justifications for this empiricism. The design and engineering experiences are very dependent on the review of previous case studies (as 'demonstration' in policy content). Usually, only the retrofit results were analysed in the project reports, hence the designers and engineers cannot acquire the knowledge and developed the systematic theory to support their selections of retrofit measures and materials.

Low efficiency: Similar to the single building scale RURB studies, current RURB projects are retrofitted and evaluated as building-by-building cases, which makes them difficult to apply for general use. For example, in the current FYPs policy content, the RURB objectives required lots of demonstration projects to be finished within five years. Yet retrofit designers must successively and individually survey and design each old residence at the single-building scale and in response to diverse local conditions. Therefore, the design efficiency is very low since there is no universal design guide or standard at the regional scale or for similar types of old residences.

Resident coordination: As reported by RURB projects, resident coordination is one of the most difficult problems. These previous project reports find that the disconnections between RURB designers and residents have caused many problems during the retrofit design. Based on the nature of urban residential buildings, the ownership of the whole building is spread over each household unit. For the retrofit measures that take place on the shared building space, such as the external walls, roof and lift, residents may not be in unanimous agreement to accept the retrofit actions. In this case, only one uncooperative resident will hinder or cancel the whole retrofit plan, even if the other 99% of residents have agreed. Therefore, the communication between retrofit designers and residents is the key issue to achieving the retrofit process.

The accumulation of previous RURB project reports reviewed has provided valuable insights to support future RURB design and research. Firstly, these projects are the empirical evidence to describe the fundamental engineering knowledge of RURB. Their ideas of successes, failures and limitations found during the design and engineering process can become archival documents for reference use. Secondly, the previous experience showed how experienced RURB designers and engineers produce the retrofit design and select the retrofit measures, equipment and building materials. Thirdly, this conventional empirical thinking can expose the current problems arising from the lack of a theoretical basis to support RURB design, the low efficiency for generalised use on an urban scale and the barrier between RURB design and the coordination of residents. Consequently, the experiences from RURB projects can help RURB professionals make appropriate retrofit policies and apply techniques in buildings with diverse building conditions and local factors, which is currently the most important reference source since there is no reliable RURB policy for designers and engineers and no developed systematic RURB theory for researchers.

2.5. Summary

This chapter reviewed the development of governmental building energy policy, academic building retrofit studies based on different scales, research applications, techniques and lessons learned from many completed retrofit engineering projects. The critiques and insights of current RURB academic studies and engineering projects have been discussed and argued to discover their achievements and problems. By reviewing published works with a similar purpose to this thesis, the building typology, urban building studies using the clustering method, the archetype aggregation method and the building simulation method were argued as reasonable and considerably effective when applied to RURB research.

These insights also provided a picture shown in Figure 2.1, which shows that the current problems of RURB policymaking are caused by the lack of feedback from retrofit designers, engineers, scholars, and residents to policymakers. RURB policymakers currently have no data source, clear definition, and systematic analysis provided by these important involved people, hence their policymaking and design process of RURB standards are hindered. Furthermore, although many scholars have made efforts to develop different approaches to increase the retrofit effectiveness, the concerns of the research scale, oversimplification risk and isolation between people from previous studies have been argued and criticised in this chapter. It was also found that RURB research needs more innovative systematic thinking to clarify systemic problems and explore possible solutions.

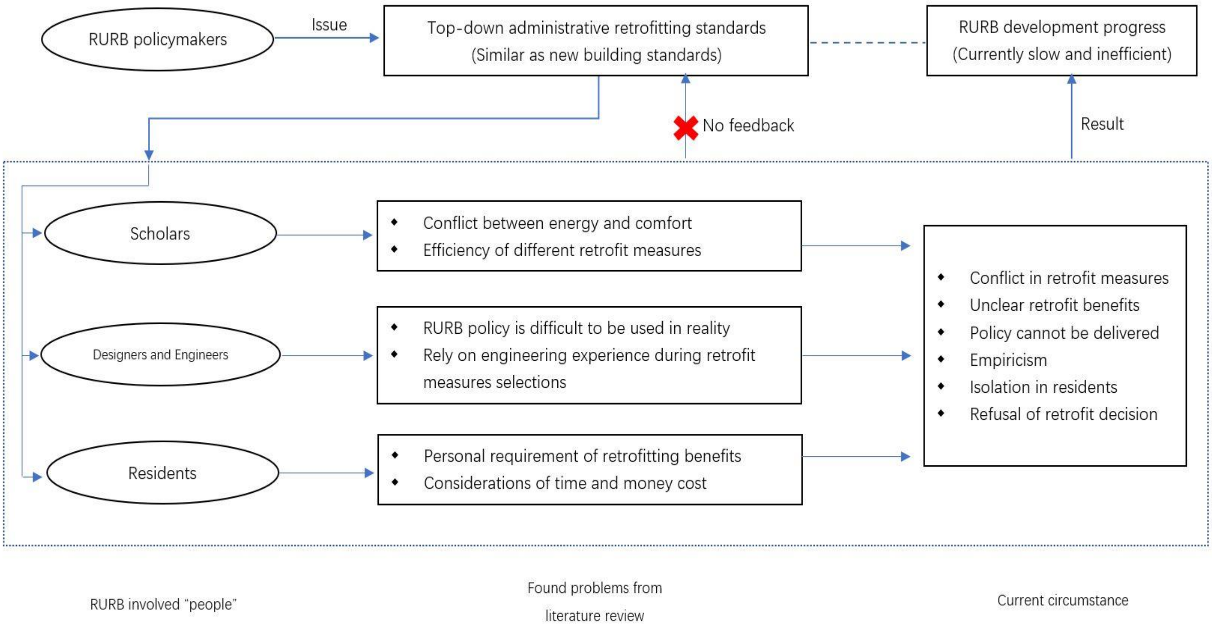


Figure 2.2: The people and problems involved in exploring RURB from the current literature

As shown in the large box at the bottom of Figure 2.2, the diverse opinions from other RURB participants and the problems found have proven that the conventional approach for new buildings - using top-down administrative policy and linear thinking for research without communication with residents - is no longer suitable for RURB. The different roles during the retrofit progress of residential buildings are currently very isolated and it is difficult for residents to make decisions about retrofit without a clear prediction of its benefits and costs. This could be the main reason which hinders the development speed of modern RURB. Therefore, a hypothesis can be established that RURB should be considered as a comprehensive system, which should be understood and analysed through relevant system thinking methods, rather than as a system of linear engineering projects.

3. Methodology

3.1. Introduction

The purpose of the methodology chapter is to present the designed structure of applied research theory and methods adopted to deliver research objectives two to five. This chapter follows the critiques and insights of RURB summarised from the literature review chapter of current RURB policy, academic studies, and project reports. They provide the evidence of research principles, research designs and selection of techniques used to design the methodology for this study.

The insights of the literature review have shown that the current problems in RURB, such as empiricism, low efficiency, and isolation, are caused by the lack of a systematic theoretical basis. To deal with these issues, Kroeze (2012) and Schweber (2015) argued that a theory based on a positivist and interpretivist epistemology can be the source of a hypothesis to address the knowledge, while empirical data can be collected and analysed to identify the solutions for social problems. Considering the problems and insights of this study with the epistemology of interpretivism (Kroeze, 2012), RURB can be argued to be currently understood individually based on the personal notions of different people: RURB policymakers, RURB scholars and RURB project designers and engineers. RURB professionals have their subjective cognition based on their knowledge and experiences (which can lead to empiricism and isolation problems). In this case, their field of vision may be limited and become a barrier to acquiring a comprehensive systematic understanding of RURB.

Therefore, using the subjective epistemology of interpretivism to describe RURB can be argued and critiqued as the reason for current problems. A rich and objective description of the RURB system should be obtained, while the notions, knowledge and experiences of all involved professionals and residents should be considered. In this case, positivism developed by Auguste Comte (Gane, 2013) has been proven to be the leading philosophical theory to describe the nature of science and law. It has been cited by Heilbron and Gogol (1995) and Schweber and Leiringer (2012) as one of the most important theories for understanding building, energy, construction, management and social research. This indicates that positivism rather than logical empiricism should be adopted as the research philosophy to describe and understand the RURB from the system perspective.

This chapter considers the system perspective of positivism as the research philosophy to reacquaint and develop the RURB system theory. Firstly, the hypothesis of RURB system thinking was established since RURB had been understood as a linear engineering task for many years. Secondly, the Bayesian notion of the inductive reasoning method is used to justify the RURB system hypothesis and definition. Thirdly, the system thinking theory behind the causal layer analysis method is adapted to provide the foundation and rich description of RURB system cognition. This chapter then further explores the process of how RURB system variables and system participants influence each other and produce knowledge of system interactions. The developed RURB system theory can argue the systematic knowledge, provide the theoretical basis for RURB design, discover the systemic problems, and find the solutions to support future RURB policymaking.

Moving on, an experiment is designed to follow positivist logic to verify the rationality and internal consistency of the developed RURB system theory. This chapter identifies the selection and design of a case study as the experimental platform by generating and analysing retrofit costs and benefits. Research methods are reflected upon and selected based on the review of current building retrofit standards, studies and practices. Afterwards, a coherent application of building modelling, field surveys, building energy simulations, calculation and multi-criteria decision-making analysis is argued to be the appropriate approach for data collection and analysis. Finally, the research ethics and originalities are discussed.

3.2. Research design

The research design follows the research questions raised and the insights argued in the review of the current literature. There are two core sections coherently designed for this thesis: 1) developing the system thinking theory of RURB, and 2) modelling a RURB case study using this theory with a system thinking perspective.

3.2.1. Understanding the RURB system

Raised as the first research question, it is the fundamental task to proceed with the RURB research without repeating the mistakes identified in the above literature review of current RURB studies and reports, including empiricism and the isolation of

RURB professionals and residents. Following the statement of the first research question, this study needs to show how the system of retrofitting in urban residential buildings (RURB) should be fully understood. The structured research steps are shown in Figure 3.1:

- Step 1: Develop the hypothesis of the RURB system and justify its system properties.
- Step 2: Identify the brief system cognition, including the system definition and system elements, which are the system boundary, system players and system variables.
- Step 3: Conduct surveys in the case study area to collect qualitative knowledge and quantitative data from RURB professionals and residents.
- Step 4: Clarify the system cognition by adapted causal layer analysis - system player analysis.
- Step 5: Explore the interactions between system players and variables to develop the theoretical basis for RURB design and to discover the systemic problems and possible solutions.

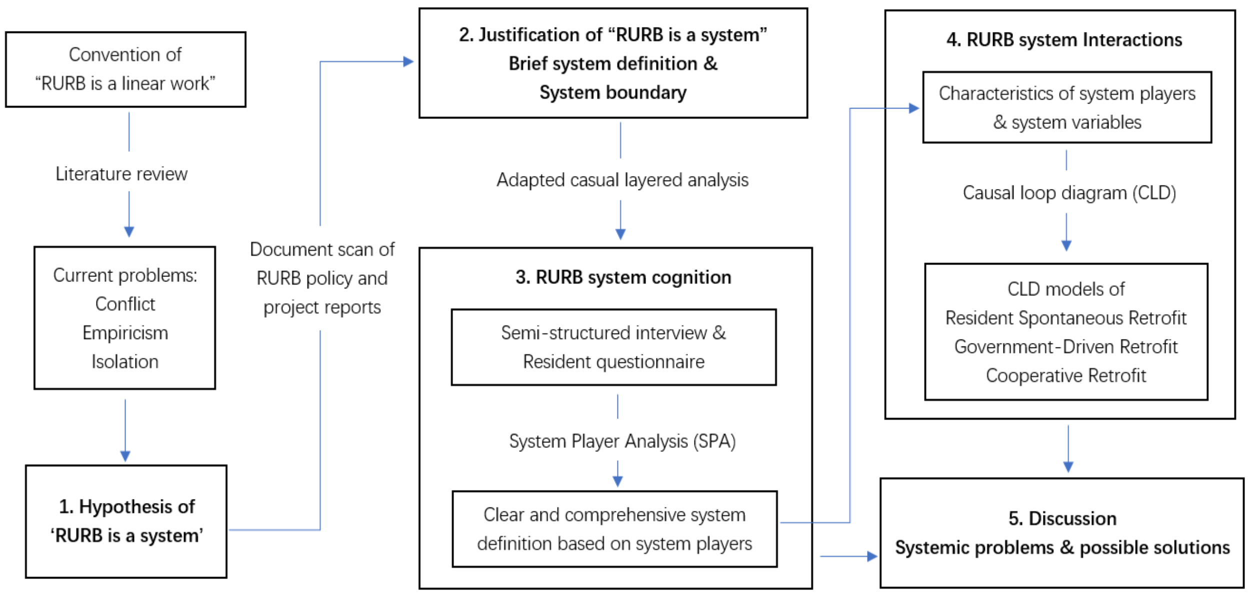


Figure 3.1: Research steps involved in the design and connections of the system thinking analysis

System justification: As argued in the literature review chapter, the current problems of RURB are caused by the lack of a "widely accepted" theoretical basis. Conventional approaches to RURB have been criticised as empirical and its current engineering logic as linear action. As indicated, the current definition of RURB is structured based on many previous project practices during its engineering development. In this case, the inductive reasoning method of positivism should be appropriate to obtain a straightforward, universal understanding of RURB. As Hayes *et al.* (2010) and Skyrms (2000) introduced, Bayesian inductive reasoning involves existing knowledge and observations to justify the induction of an unknown truth or the prediction of a certain fact. Historical examples discussed by Hacking (2001) prove that inductive logic can be used to introduce complex empirical science to form a universal scientific judgment. Therefore, the 'RURB is a system' hypothesis can be raised based on the accumulation of existing engineering practices and be justified by the logic of inductive reasoning, with a brief judgement on the system definition.

System cognition: Once RURB has been justified as a system, it is necessary to select the appropriate system-thinking theory to analyse the system cognition and inner system elements to produce a clear definition and comprehensive description. By reviewing literature from Assaraf and Orion (2005), Forrester (1994), Werhane (2008), Haraldsson (2004), Tranfield et al. (2003), Williams et al. (2017), Maani and Cavana (2007), Sterman (2002), Jackson (2003) on system thinking approaches and the review of research and theories by Williams *et al.* (2017), it is found that system boundary, system dynamic and soft operations research are typical theories that aspire to understand and improve the systems. In this case, Causal Layered Analysis (CLA) has been selected as the suitable research method to obtain the required system cognition. The details will be discussed in the next chapter.

System interactions: Afterwards, the second research question should be answered: 'What are the relevant connections between RURB professionals and residents for aspects including retrofit policies, designs, engineering works, retrofit techniques and retrofit benefits and costs?'. To further analyse the RURB system and explore its systemic problems, the Causal Loop Diagrams (CLD) system-thinking approach is found to be an appropriate method of providing visual diagrams of structures and elements, especially for very dynamic and complicated systems (Haraldsson, 2004, Forrester, 1994). CLD is a popular method of describing, organising and simplifying a system with a very complex nature.

Relatively, the study from Haraldsson (2004) showed three main elements - variables, causal links and feedback loops - for the CLD analysis. With the variables and links defined, feedback loops act as reinforcing and balancing loops that may amplify or dampen the effects of changes, moving the system away from or towards the equilibrium point set according to the purpose of the research. This CLD system-thinking approach has proved to be a great assessment tool for policy interventions, decision-making and renovation effect evaluations (Aikenhead et al., 2015, Paterson and Holden, 2019). Therefore, the designs of RURB scenarios can use the CLD method to represent the system interactions between retrofit variables (such as retrofit objectives and limitations) and system participants (on their retrofit demands and initiatives), which can be more reasonable compared to the conventional retrofit designs based on empirical inferences.

3.2.2. Case study

Since the previous section clarified the system cognition and interactions of RURB, the rationality and efficiency of this system theory as positivist research should be verified. For urban-scale building research, it is impossible to construct a zone of experimental urban buildings due to time and cost issues. Therefore, the case study and urban building modelling methods should be applied to obtain and analyse the retrofit effects based on the proposed system thinking theory. Thus, a RURB case study is developed as an experimental platform project in this thesis. As a proving process, a summary of the research steps in the case study is listed below with the research method map shown in Figure 3.2:

- Step 1: Select the case study zone of urban residential buildings.
- Step 2: Determine the reference buildings and their building properties and conditions.
- Step 3: Conduct a field survey in the case study area to identify RURB criteria and local conditions (together with the above system thinking analysis as presented in Chapter 4).
- Step 4: Design retrofit scenarios for the building energy simulation based on the

identified RURB system and survey results (presented in Chapter 4).

- Step 5: Calculate all relevant quantitative retrofitting criteria, including energy saving, retrofit cost, the time required for retrofit and the improvement of accessibility (lift), safety (fire and lighting) and comfort (air quality).
- Step 6: Apply the Muti-Criteria Decision-making (MCDM) method to each retrofitting criterion and retrofitting scenario. Discussion of the MCDM results to make suggestions for RURB policymaking.

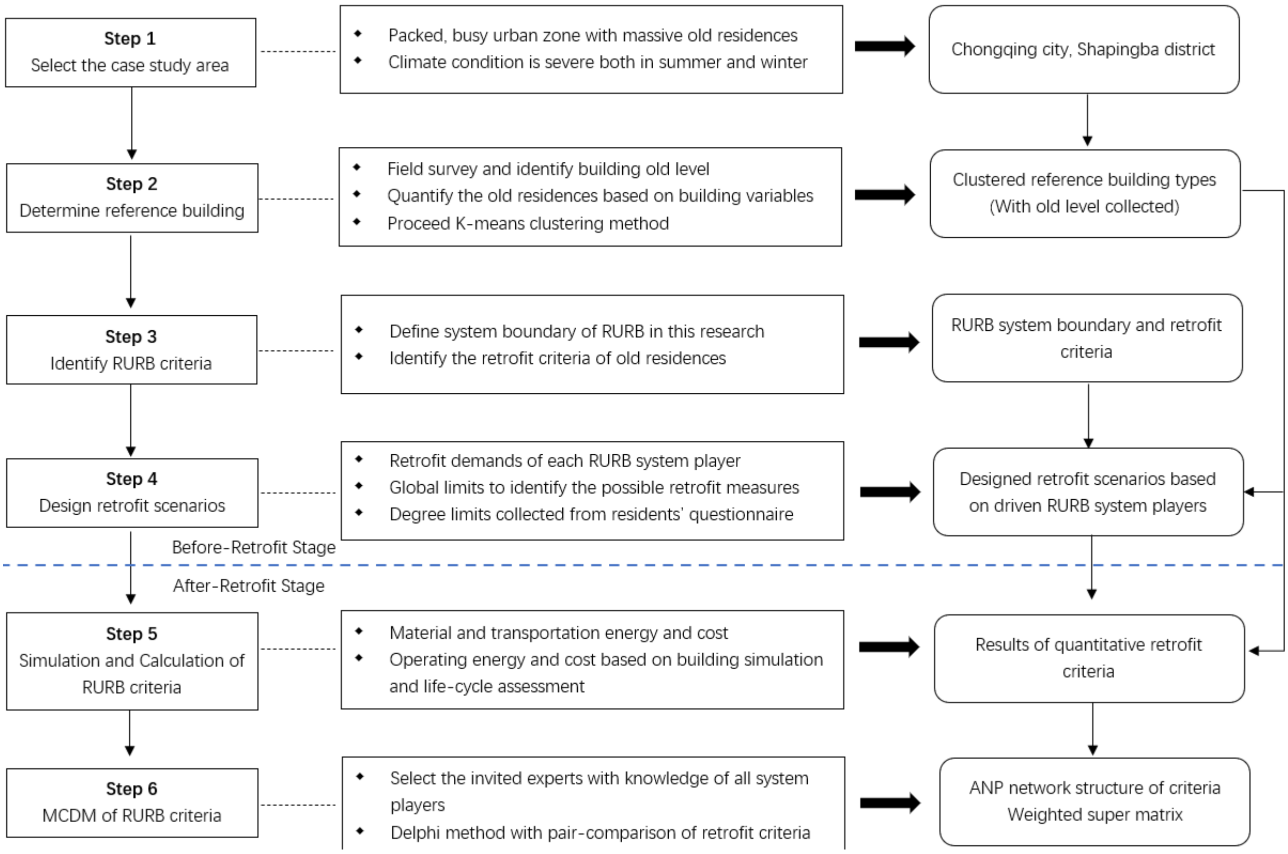


Figure 3.2: Research steps for the design and connections in the case study section

There are two sub-sections delivered to answer the third and fourth research questions in the case study section:

Before retrofit: By observing the previous RURB design and engineering process, two sections can be identified as *the before-retrofit stage*, which will be obtained from research design steps 1-4. Firstly, the description of the current conditions of old residences is necessary to understand the retrofit variables including the current building performance, functionalities, built age, materials, structures and the actual age of old residences, as well as a possible library of retrofit measures and the retrofit desires and opinions of residents. This is the 'description stage' for the later retrofit design, in which the survey and building modelling methods should be applied.

Secondly, the retrofit scenarios (also called retrofit bundles and packages in different studies and projects) should be designed by appropriately selecting the retrofit measures, techniques, equipment, energy control methods and use of materials that need to be integrated. Different retrofit scenarios may be designed to achieve the corresponding retrofit objectives. They should also acknowledge the limitations of the retrofit budget, techniques and residents' demands. This is the 'retrofit-design stage' for the later retrofitting process which should be progressed by building-energy simulation and calculations. In summary, the retrofit scenarios are designed to follow the identified RURB system theory with system interactions between variables and system players as revealed by the CLD method (see section 3.2.1).

After retrofit: Following the logic of positivism, the developed RURB system theory and retrofit scenario designs should be verified by a quantitative analysis of retrofit results. Therefore, *the after-retrofit stage* is presented through building energy simulations and calculations based on the retrofit scenarios as the building models of old urban residences. This corresponds to the fifth and sixth research steps as explained in Figure 3.2.

Due to the scale of RURB research, the data obtained should contain both 'total' and 'unit area' results for the retrofit benefits and costs in the case study area. The quantitative retrofit benefits and costs can be classified into different retrofit criteria, such as i) retrofit investment energy; ii) retrofitted operation energy; iii) retrofit investment cost; iv) retrofit time cost and v) retrofitted operation cost. The qualitative retrofit benefits can be defined as vi) indoor comfort improvements, vii) functionality improvements and viii) safety improvements. Then, to discuss and evaluate the value of retrofit scenarios, the multi-criteria decision-making analysis is introduced to weigh the retrofit effects.

3.3. Data collection method from RURB professionals

3.3.1. Interviews

Since the causal links and feedback within the RURB system are linked to four groups of people, it is necessary to apply an appropriate approach to collect the relevant RURB information from them. Among many methods are a census, interviews, polling and questionnaires which apply social science to building and construction science (Oppenheim, 2000). The questionnaire survey method is very well-developed and is widely considered to be an efficient way of quantitatively collecting considerations, preferences, opinions, behaviours and factual information (Moser and Kalton, 2017, Hu et al., 2019, Zhang et al., 2018). Meanwhile, the interviewing approach can be an effective method to formally collect social information from professionals for research purposes (DiCicco - Bloom and Crabtree, 2006, Holstein and Gubrium, 1995, Merton, 2008, Oppenheim, 2000).

However, to integrate building policy, designs and retrofitting engineering, and residents, Fellows and Liu (2015) discussed the research methods for RURB construction works and infer that the conventional field survey approach may not be enough because of the multiple criteria and people involved in residential buildings. Therefore, a combination of social techniques should be applied in this study. For example, Pan and Pan (2019) provide a successful social study that combined three social techniques - interviews, focus groups and questionnaires - to evaluate the opportunities and risks of implementing a zero-carbon building policy in Hong Kong city, which could be a great model for the similar steps needed when collecting information from professionals and stakeholder concerning building retrofit policy.

As argued in Chapter 2, it is essential to collect and acquire realistic and reliable information from both RURB professionals and residents, which is highly insufficient under the current circumstances. In this study, two survey methods - interviews and questionnaire surveys - are selected for the collection of data on RURB experiences, opinions, knowledge and preferences for retrofit measures, which will become evidence and a reference for future RURB policymaking.

For this study, after the RURB system is justified, the relevant positive and negative elements must be quantitatively analysed with the information provided by the core system participants – as system players. To acquire the information needed from professionals, the semi-structured interview method is used to collect valuable opinions, experiences and knowledge from RURB policymakers, designers and engineers and university scholars, which has been proven as an effective approach while the collection process will be person-to-person to reliably collect qualitative data (Holstein and Gubrium, 1995).

3.3.2. Review **of semi-structured interviews for building energy studies**

To robust more effective retrofit policy recommendations from RURB system players, Galvin and Sunikka-Blank (2017) proved that qualitative information and data collected by using social science approaches could be extremely important. For collecting detailed qualitative information related to unique social conditions from professionals such as policymakers, retrofit designers and engineers, an appropriate approach to data collection method should be carefully applied.

In this case, studies from Merton (2008) and Oppenheim (2000) proved that the focused interview method seems to be a more effective approach to be applied among many approaches of opinion and experience data collection. Moreover, a series of survey method studies including McCracken (1988), Holstein and Gubrium (1995), and DiCicco - Bloom and Crabtree (2006) were reviewed, their active survey method, discussions and results have shown that the interviewing approach is also a remarkable method to formally collect the social information from professionals for research purpose.

As indicated, the semi-structured interview method has been proven as a more simple, efficient and practical way to collect qualitative data from skilled respondents, who are professionals in their specific research or industry area (DiCicco - Bloom and Crabtree, 2006, Oppenheim, 2000), as well as in building energy and retrofit studies (Davies and Osmani, 2011, Pelenur and Cruickshank, 2013). This technique can bring high validity and is useful for discussing and clarifying complex questions or issues (Merton, 2008). Hence it should be selected as the key method to collect accurate local conditions in the RURB system from local policymakers and experts. Combined with the four system players section mentioned in the previous literature review, three types of objective and qualitative data should be collected from local professionals: governmental support, the motivation of residents, and technical support.

3.3.3. Interview questions design

According to the main RURB system player-defined, governmental policymakers, designers, engineers, and scholars have been identified as important 'professionals' in the system. They can provide more deep, accurate and valuable information relevant to policymaking, professional knowledge, or design and engineering experience in the field. Following the logic of positivism, objective RURB knowledge and experience from three groups of professionals are collected through personal face-to-face interviews.

The Semi-structured interview questions are carefully designed relevant to the roles of the interviewees. Four sections of questions are provided during the interview. Section 2 of policymaking is optional for interviewed engineers, while section 3 of retrofit engineering is optional for interviewed governmental workers. Section four, however, has more open questions designed to ask about RURB social issues and current difficulties. A brief introduction of the interview sections is shown below, and the full interview question design can be found in Appendix A.

1) Section 1: educational background, work experience and role of organisation

At the beginning of the interview, a sense-making conversation is necessary to open the mind and get close to the interviewees, before asking professional questions.

- Q1: Sensemaking: Asking about education and job background, general description of role and organisation, and career so far of the building retrofitting.

2) Section 2: knowledge and experience in RURB policymaking

In this section, experienced policymakers are interviewed to collect their opinions about the current functioning policy system of the RURB. Structured four questions of 'current situation', 'evaluation', 'challenges' and 'local issues' are introduced to have a comprehensive understanding of China's RURB policy system in history, in current circumstances, and in the specific local urban area. Accordingly, possible development and improvements in future could be inferred from the information collected. Their professional experience can also provide guidance for RURB retrofit designs closer to the modern retrofit requirements from the government.

- Q2: Current: Asking for professional knowledge of current China's RURB policy system, including policy structure, responsibilities, and procedure of design and implementation steps.

- **Q3: Evaluation:** Asking about achievements, critical problems, and personal opinions about the effectiveness of the current RURB policy.
- **Q4: Challenges:** Asking current found challenges and possible improvements from personal experience in the design process of RURB policy.
- **Q5: Local:** Asking approaches and patterns of financial support for RURB from the local or national government, and personal opinions for possible future patterns.

3) Section 3: knowledge and experience in RURB design, engineering, and studies

Professional designers, engineers and scholars of building retrofit are interviewed with specifically designed questions in this section. Four structured questions are raised to collect their personal experience and knowledge in building retrofit design, engineering procedure, and efficiency of building retrofit measures. More importantly, local factors such as climate, living culture and economy are asked to collect unique thinking from experienced professionals, which future RURB design and policy can take the local advantages and become more effective.

- **Q6: New and Old:** Asking index of design standards and realistic performance between current new residential buildings and retrofitted residential buildings.
- **Q7: Procedure:** Asking about their own understanding of engineering procedure or studies of top-down government-driven RURB and individual resident-driven RURB, and their differences in pattern and effectiveness.
- **Q8: Efficiency:** Asking personal opinions about current RURB efficiency and problems, and how to increase engineering efficiency as much as possible in future RURB.
- **Q9: Local:** Asking for personal opinions or experiences of important, unique local characteristics should be considered during RURB design and engineering (including climate, culture, economy, local citizens' behaviours, building material, etc.).

4) Section 4: social and motivation problems and solutions

After the structured sections, the questions related to social issues and the current difficulty of RURB are comparatively open and flexible as brainstorming. Based on their personal feelings and experience, this section aims to collect valuable inspiration and suggestions from interviewees. Three questions are roughly designed corresponding to their role in RURB career, as previously discovered difficulties for policymakers; hypothesis of RURB design in interviewees' mind for designers and engineers' own home; and potential conflicts between thermal comfort requirement and energy consumption for building scholars. However, these open questions may not be strictly asked depending on the previous interview process.

- **Q10: Difficulties:** Asking about difficulties found by professionals which prevent residents to retrofit their homes (cost, time, trouble, noise, availability of living place, material), and things can increase the retrofit desire residents.
- **Q11: Hypothesis:** Asking personal considerations of retrofit measures from professionals' own homes, and personal preferred help and support from the government.
- **Q12: Conflict:** Asking personal opinions of conflicts between increased indoor living comfort and energy conservation, and the weight or how to balance them.

In summary, Q1 is asked of all three roles of interviewees as 12 people at the beginning, Q2 to Q5 are asked of policymakers, and Q6 to Q9 are asked of designers, engineers, and scholars. Later, Q10 to Q12 are open questions related to social issues and asked all 12 interviewees with minor adjustments by the interviewer depending on the proceeded conversation. Based on the reality of invitation difficulty, time and cost, policymakers had shorter time interviews 15-20 minutes for each person; designers, engineers and scholars had 45-60 minutes interviews and had longer discussions about local and social issues.

3.3.4. Selection of interview respondents

Based on the natural difficulty and cost of inviting, communicating and persuading professionals to work in high places, the selection of interviewees is the most important step for the survey. The research from Galvin (2014) has studied 54 published interview studies on the building energy consumption aspect, and its straightforward statistical result has proven that 12 interviews can largely achieve saturation of information required for research objectives. Considering the limitation of research time and funds, a total of 12 professionals of RURB career, disturbed evenly as 4 of each RURB role, were selected and invited for the interview of this study, as shown in Table 3.1. All 12 interviews were taken face-to-face, and the agreement of anonymization and data protection are informed or signed before the interview. Following the time allowance discussed, the policymakers had their interview finished within 15 minutes, and designers, engineers and scholars had more flexible interview times between 30 to 45 minutes.

Table 3.1 Selection of interviewees

No.	Current role	Career place	Role of RURB
Policymaker			
1	Retired officer	Ministry of Housing and Urban-Rural Development	Policymaking
2	Officer	Ministry of Housing and Urban-Rural Development	Policymaking
3	Officer	Ministry of Housing and Urban-Rural Development	Policymaking
4	Officer	China Academy of Building Research	Standard design
Designer & engineer			
5	Director	China Coal Science and Industry Group - Chongqing Design and Research Institute Co., Ltd	Retrofit plan design
6	Designer	China Academy of Building Research	Retrofit standard design
7	Designer	CSCEC Southwest Design and Research Institute Co., Ltd	Retrofit plan design
8	Engineer	Country Garden Holdings Co., Ltd	Retrofit construction
University Scholar			
9	Professor	Chongqing University	Building standard
10	Professor	Chongqing University	Thermal comfort
11	Associate professor	Chongqing University	Retrofit measures
12	Associate professor	Beijing University of Civil Engineering and Architecture	Retrofit measures

3.4. Data collection from residents

3.4.1. Questionnaire survey

For residents, scholars have found questionnaire surveys to be a very effective research method to collect qualitative opinions and quantitative data on, for example, building energy, indoor thermal comfort and indoor environment retrofit (Jiang *et al.*, 2020). As RURB involves residents and their diverse opinions of the RURB system, the questionnaire survey could be the most appropriate method to collect information from residents, based on its ability to randomly collect large amounts of data from a large number of people (Krejcie and Morgan, 1970, Zhang et al., 2017). Therefore, for collecting the data and opinions from residents, the questionnaire survey method is used for this study. Given the diverse features of residents' considerations about RURB, the sample size must be large enough to be representative and to reduce errors (Krejcie and Morgan, 1970).

To acquire the RURB information concerning residents' opinions, questionnaires were distributed in the selected case study urban area. Following key literature reviewed from Oppenheim (2000), Moser and Kalton (2017), Grosh and Glewwe (2000) and Miles *et al.* (1994), the questionnaire in this mixed method study was designed to collect two types of data - 'the number and the word' - as quantitative and qualitative data.

Quantitative data: 'Number' is based on the theory from Oppenheim (2000) and Moser and Kalton (2017), opinion-based survey data from large random groups of people should be direct to the subjects and easy to understand. This part of the questionnaire design should consist of single or multiple-choice questions to collect quantitative information from residents, such as basic building information, energy bills, indoor energy equipment, thermal comfort and retrofit cost felt to be affordable.

Qualitative data: 'Words' as opinions from random people may be very diverse, but also important. For example, retrofit designers must know if residents want to introduce new systems or devices before they provide information on equipment efficiency and ask them to choose. In a separate case, Grosh and Glewwe (2000) provided a great exemplary questionnaire for households in developing countries. In this RURB study, questionnaires are supposed to collect qualitative data on the "desire for retrofit" based on Grosh and Glewwe's experience, including the building components residents prefer to retrofit their living environment and the indoor equipment residents prefer to replace or upgrade.

3.4.2. The questionnaire survey in this research

This section presents the social survey method and work of a questionnaire survey to collect realistic and reliable building retrofit information and opinions from the other RURB system player - residents, who were criticised to be neglected by RURB policy and studies. Initially, the detailed design of the questionnaire, survey information, and corresponding survey validation process are explained. Afterwards, the survey results are collected and analysed to acquire the conditions of old residential buildings, the retrofit demands and priority, and the current acceptable allowance range of time and financial cost issues. Finally, the results between the semi-structured interview and questionnaire survey are discussed and argued to explore the knowledge and demand gaps between RURB system players.

The designed questionnaire survey is carried out in Chongqing, Shanghai, Hangzhou, Chengdu, Wuhan, Hefei, and Changsha, seven big cities located in the HSCW climate zone in China to be an exemplar case. The conditions of old residences and the climate in this zone are both relatively bad and complicated (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2010b): old urban residences in the HSCW zone have no central heating system in the cold winter compared to northern China, but the average air temperature can be low as 5°C. The summer can be extremely hot over 40°C. Therefore, residents who live in the old residences in this zone suffer poor thermal comfort and may have a strong demand to have their homes retrofitted, which their opinions can be useful to evidence future RURB policymaking.

3.4.3. Questionnaire design

The questionnaire is designed based on two main parts and divided into six sections of quantitative and qualitative questions. Sections 1 to 4 collect necessary and realistic data on current old residences from the view of residents, including building information, thermal comfort, energy use, and opinion of retrofit cost of their old home. Sections 5 and 6 are more open and qualitative questions to ask for the unique and individual retrofit desire, and the cooperation level from residents. The detailed questionnaire is shown in Appendix B.

1) Basic information

From the review of RURB policy and literature, it could be found that the definition of ‘old residential building’ is still not clear in policy content. Since building types, built age and occupants are proven that they have a significant influence on energy consumption, it is fundamental and essential to collect basic residential building information from surveyed residents. In this section, 6 questions are set for basic information on building location, building type, area number, occupant number, lived time, built age, and retrofit frequency of the surveyed residence.

2) Thermal comfort

As thermal comfort situations could be unique and diverse in old residences depending on building conditions and occupants, 4 questions are introduced in this section to collect the thermal comfort feelings. Since comfortable and modern HVAC equipment is usually lacking in old residences, these questions ask residents about their thermal comfort feelings in hot summers without cooling equipment, as well as in cold winters without indoor heating equipment. Furthermore, desired new HVAC equipment during future retrofit is also asked to acquire the average preference of surveyed residents.

3) Energy

For residents, the cost of electricity and gas bills is the most direct feedback from indoor energy use. In China, interviewees have mentioned that the average energy use is low because residents have a late response to thermal comfort requirements compared to the rapidly developed national economy. Policymakers and scholars believe that the majority of residents still live outside of the thermal comfort zone and have very economical operation in heating and cooling equipment, even in hot summers and cold winters. Therefore, questions related to energy bill cost and energy-saving retrofit measures are designed to verify and attempt to find the true thinking about energy use and cost from residents.

4) Cost of money and time

In conventional studies, cost management of building retrofit is usually considered after the simulation or retrofit design is finished, while the retrofit measures are already applied. However, this thinking was argued that it ignores the economic burden and social issues of the residents. This kind of retrofit design sometimes provides retrofit suggestions that residents cannot or do not want to afford although they may have good performance in energy conservation. Therefore, this survey study also collects opinions about the cost management issue from residents, which can provide basic and average economic information ahead of making retrofit design and policy suggestions. Meanwhile, the time cost is another important negative factor to RURB development but is always ignored during the consideration of retrofit engineering design.

5) Demands for retrofit, and coordination

In the view of urban residents without comprehensive knowledge of building retrofit, building energy and environment, a bundle of thinking as 'desire of retrofit' from residents is identified for other considerations out of the five factors above, including residents' concerns such as government support, retrofit risks, and feeling of waste about indoor equipment replacement. The desire for retrofit is a much more complicated factor to be quantitated, but it has a significant influence on residents for retrofit decision-making. In this survey, the desire for retrofit is collected by asking residents about simulation questions with hypothesis retrofit scenarios defined by the questions.

6) Knowledge of retrofit

This section is added after the interview results are analysed. As more than half of the interviewees have mentioned the majority of residents have little retrofit knowledge and awareness of energy saving and thermal comfort, it is necessary and could be very interesting to verify and compare these personal opinions by directly asking residents about their knowledge and concepts of retrofit. Finally, an overall summary question 34 is designed with multi-options at the last of the questionnaire. It asks residents about their preference for retrofit results and imaged pictures of retrofitted homes.

3.4.4. Sample size and survey information

1) Sample size

The non-repeated sampling of the questionnaire survey in this study uses the theory developed by Krejcie and Morgan (1970) to calculate the minimum sample size using equation (1) below, which the theory has been widely applied and used for the social questionnaire survey studies for 50 years.

$$n = \frac{Nt^2 p(1-p)}{N\Delta_p^2 + t^2 p(1-p)} \qquad (1)$$

Where,

n - the sample size.

t^2 - the statistical values associated with the desired level of confidence, N - the population of each surveyed city,

p (1-p)- variance of the proportion of the population,

Δp---- the margin of error (%).

This questionnaire survey is a non-repeated sampling. The confidence level statistic: t^2 is 3.841 according to the value of the Chi-square test table when the confidence is 95% and the degree of freedom is set as 1. The sampling error range Δp is set to 5%. Since it is impossible to determine the proportion of the collected sample size to the total population of each city, the variance of the proportion of the population: p is set as the maximum value of 0.5 (Krejcie and Morgan, 1970). The total city population: N is determined as Shanghai, Chongqing, Chengdu, Wuhan, Changsha, Hefei, and Hangzhou according to surveyed cities.

The sample size is calculated using the statistics of the urban population of these seven cities. As this calculation method has little difference when the n value is massive, the maximum calculated value of 384 sample size is too low compared with the empirical rule of determining sample size, which needs to be amended. Considering the huge sample with a total population of more than 80 million, and the similar climatic conditions of each city, the target sample size of this survey is increased to 1100 while the sample size of each city is no longer strictly required to be evenly distributed.

2) Online questionnaire collection

Due to the current COVID-19 pandemic, a face-to-face questionnaire survey is not appropriate under the national control measure. It is very difficult to obtain legal permission because it may cause gathering risks for citizens. Therefore, the online mobile application – Questionnaire Star on WeChat software is used in this study to collect questionnaire answers, while several posters are placed at the entrance and around some old residential communities in different selected cities.

Meanwhile, there was a preliminary survey with 50 samples delivered to the family members, colleagues, and interviewed professionals of the researcher who can have patient discussions and get feedback to improve the draft questionnaire design. After several adjustments were applied to the final questionnaire, then the official survey was launched from April 2021 to July 2021 which a target of 1,100 samples.

The summarised questionnaire survey information is shown below:

- Survey targets: residents are living or have lived in the old residences for more than 3 years
- Survey location: seven provincial capitals of the HSCW zone: Shanghai, Chongqing, Chengdu, Wuhan, Changsha, Hefei, Hangzhou
- Designed sample size: 1100
- Data collection method: online questionnaire via WeChat mobile application
- Preliminary survey: 50
- The total questionnaire collected: 1100
- Final valid questionnaire: 1021
- Survey time: April 2021 to July 2021

3) Validation

The preliminary survey is not accounted to the official survey, and the total questionnaire collected is 1100. Later, all results are input to SPSS-AU software for validation, as this online SPSS tool can provide faster validation results hence new residents can be quickly invited and filled with the invalid result removed. Following the attribute of different questions, scale questions including Q7, Q8, Q11, and Q12 have reliability analysis based on Cronbach's Alpha method (Pallant, 2013, Nie and Norman, 2003) and have a reliability coefficient of 0.68, which is acceptable (Eisinga et al., 2013).

All other single-choice questions have validation tests conducted after the survey to examine the reflection ability of designed questions based on the KMO test (Chung et al., 2004), and have the coefficient value of 0.63 to 0.91 based on different sections which are acceptable as qualitative questions of residents' retrofit desire and cooperation have only 2-3 options for choosing. Furthermore, all qualitative single-choice questions have abnormal values and invalid sample checks of their answers (project, 2016). A 70% same-answer testing is set to select and remove inefficient questionnaires from the results. At last, there is 1021 valid and efficient questionnaire result to be analysed.

3.5. Data collection of building modelling

3.5.1. Field survey

As the literature review section argued, the majority of conventional building retrofit studies and simulations only consider and use building design parameters provided by the national building standards. Since Baynes and Wiedmann (2012) have evaluated the oversimplification risk and problems of the building-by-building scale of the conventional approach to building simulation, RURB designers and engineers must carefully consider and collect information on simulation input parameters. The reliability of the building modelling process is the key to providing more trustworthy results for policymakers and residents.

Therefore, a field survey is necessary to collect realistic data on physical building conditions and façade parameters. Considering the number of floors in a building and the external window form are very conspicuous representations of a building's age based on past limited economic and construction techniques, collecting these two variables is necessary. As well as the windows, the greatest impact on the indoor cooling and heating load comes from the building façades. Furthermore, compared with new buildings, the old buildings have many quantifiable old characteristics, such as wall corrosion and no thermal insulation. While the definition of 'old' is difficult to clearly define, it is necessary to quantify the 'old level', because there is no official design manual or building standard that can be referred to that describes and quantifies 'ageing'. 'obsolescence' or 'deterioration' of the building façade, built environments and lack of functionality.

3.5.2. Documents

Similar to the current literature reviewed in Chapter Two, archival documents on policy, studies and project reports are valuable and useful data sources to provide evidence of current knowledge of RURB. Based on the Bayesian philosophy of logical inductive reasoning, exhaustive fact-testing, evidence from documents and concluded experiences are the most important references to provide a rich description of current inferences about RURB for this study (Hayes *et al.*, 2010). Therefore, more documents related to the local aspects of RURB should be reviewed and discussed to understand the development and current circumstances of RURB policymaking, case designs and engineering approaches.

Moreover, when collecting the necessary primary data from social surveys and field surveys, it is unavoidable that some data cannot be manually acquired because of the limitations of time, cost and opportunity. Therefore, secondary data from documents and archives (as in building policy and building design standards) is also necessary for RURB simulation research. Since it has been argued in the literature review section that the current RURB policy may have had problems with outdated and local limitations during its development history, it should be carefully reviewed and examined to select the most appropriate design index to ensure the reliability of the retrofit modelling results.

3.5.3. Building typology

For urban scale research, fully describing all the accurate building models in the case study city area is argued to be impossible because of the complexity and time-consuming nature of the task (Dascalaki *et al.*, 2011). Yet, oversimplification is also revealed as a serious problem from the review of current RURB studies. Therefore, to balance the influence of over-elaborate details and oversimplified models, it is necessary to scientifically describe and simplify the studied building models by classifying them into different representative building types, as in the ‘reference buildings’ concept. Based on the reviewed successful examples from Li *et al.* (2018b), Famuyibo *et al.* (2013) and Elci *et al.* (2018), urban residential reference buildings can be obtained by using clustering analysis or aggregation approaches based on satellite images. Accordingly, building typology should be a mandatory research step for bottom-up building research on an urban scale, particularly in building models that rely on data collection by field surveys and document analysis.

3.6. Building Energy Modelling (BEM)

To deliver the RURB results with set retrofit scenarios based on the different objectives or purposes, a method is required to calculate the retrofit effects. Considering the large urban scale with many buildings and information, it is impossible to construct an experimental platform and proceed with measurements that collect data for RURB research. Therefore, the computer simulation of BEM techniques may be the only approach that can simulate the retrofit process. In this case, a simulation platform must be found or developed while a literature review of the development and abilities of modelling and simulation methods should be provided.

Based on the nature of building retrofit, retrofitting research needs two mandatory stages: ‘before’ and ‘after’ to provide data for effectiveness analysis (Murray et al., 2012). Because of its effectiveness for time and cost-consuming issues, Reinhart and Davila (2016) stated that the building simulation method has been proven as the most appropriate approach to effectively provide ‘after’ retrofitted results based on ‘before’ baseline scenarios for building retrofit analysis. After reviewing the building simulation studies for retrofit purposes, computer simulation is especially necessary for urban-scale building retrofit in which complex retrofitting variables are applied to designed models.

To generate the data for the retrofit criteria for operating energy consumption - the Energy Use Intensity (EUI) - using the building energy simulation tool based on the bottom-up analysis of retrofit results at the urban scale is the most appropriate approach. Building energy simulation software is widely proven the best and the most practical method of acquiring the EUI data for large-scale building energy research due to its time and cost-effectiveness during data generation compared to experimental methods. For this study, the *EnergyPlus* platform together with *OpenStudio* and *SketchUp* software is used for the building modelling process and building energy simulation.

3.7. Multi-Criteria Decision Making (MCDM)

The simulation and calculation results of retrofitted scenarios could generate a higher quality of data for aspects, such as energy consumption, material flow, carbon emission and thermal comfort improvements. They can be classified as ‘benefits’ and ‘costs’ and defined as different ‘retrofit criteria’. Accordingly, a result evaluation approach based on decision-making analysis with multiple retrofit criteria should be selected to analyse the retrofit results and find the most appropriate designed scenario - as it is the ultimate aim to provide an ideal (or the best) retrofit plan which meets the demands of all RURB system players.

Among many MCDM theories, the Analytic Network Process (ANP) of Saaty has been proven effective in dealing with dependencies whilst the Analytic Hierarchy Process (AHP) is better for MCDM with more independent criteria (Saaty, 2013) with its additional concepts of "control layer" and "network layer". ANP can provide more realistic and accurate results while the criteria are correlated and it can model feedback loops using clusters with inner dependency to replace the liners in the AHP method. The ANP method has been proven useful for building energy retrofit evaluation, such as by Liu et al. (2018a), Xu *et al.* (2015), Pakand and Toufigh (2017) and Moazzen *et al.* (2020). For this research, ANP could be more suitable based on the complex nature of the element relationships since the majority of retrofit criteria are interconnected. For example, the higher investment cost can lead to better retrofit results to reduce building operating energy consumption and to reduce operating energy cost; however, it will increase the investment energy consumption of retrofit materials (Ishizaka and Nemery, 2013).

3.8. Research ethic

During the social survey process, participants will have to invest in RURB-related issues of time, energy, and financial resources with other people. Therefore, ethical issues should be carefully considered during the survey design. For a reflection on ethical matters, the method of Miles *et al.* (1994) which provides comprehensive theory and practice for the ethical issues for survey research-oriented professions is reviewed. In this research, the following ethical elements will be addressed during the RURB survey design: worthiness, competence, informed consent, benefits, costs, reciprocity, harm and risk, honesty and trust, privacy, confidentiality, anonymity, intervention and advocacy, research integrity and quality, ownership of data and the conclusion and the use or misuse of results.

Accordingly, to avoid data leaking, all data will be saved on a password-protected laptop to which only the researcher has access. To protect privacy, all information collected in interviews and questionnaires will be anonymous. The researcher will make sure all surveyed people are comfortable and voluntary participants. Interviews will be conducted in a quiet and safe environment outside the workplace to encourage them to be more open to expressing their feelings and critiques. Additionally, to avoid the influence of the recent COVID-19 pandemic, researchers and interviewees will follow the related rules on wearing face masks and maintaining safe social distancing during interviews.

3.9. Research Originality

While the shortages of conventional research approaches have been criticised and argued in the literature review section, this study develops the original research aspects below to avoid similar experiences and further increase the reliability, effectiveness and applicability of RURB.

Table 3.2: Originality of this research

Conventional approaches for residential building retrofitting	This thesis of RURB
◆ Consider building retrofit is a linear engineering action proceeded by designers and engineers.	◆ Develop the RURB system-thinking theory by justifying the RURB system, clarifying the RURB system cognition, identifying the four main system players and analysing the system variables, causal loops and feedback to explore systemic problems and solutions.
◆ Use single-building-scale modelling or use a stock statistical database.	◆ Use urban-building-scale modelling and analysis as the case study.
◆ Use oversimplified 'box building' models or the overcomplicated pure physical geometric models.	◆ Apply building typology to classify the representative building types in the urban area.
◆ Design retrofit scenarios based on building standards only or setting a result target and choose the techniques causally.	◆ Collect specific local condition data from the four players through social survey methods and provide evidence for more reliable RURB scenario designs.
◆ Compare the retrofitting result with different sensitivity models and choose the best practice.	◆ Apply the MCDM method to analyse the different results of different scenario settings and provide qualitative and quantitative evidence for future RURB policymaking.

With the originality of this research in Table 3.1, a more reliable and ideal retrofitting scenario should be established. This scenario will be coordinated by the specific local RURB system players and conditions, which can evidence the future RURB policymaking in this region. This method could be systematised and become a common approach for all cities to evaluate their RURB potential and find solutions to quicken and improve RURB progress, which could be one of the contributions to current knowledge.

3.10. Summary

This chapter discussed the rationale of the research methodology designed and used in this thesis. Firstly, this study challenged the current subjective knowledge of RURB based on the critiques and insights from the literature review. It was asserted that the RURB system thinking should be the appropriate theory for a rich, systematic description and understanding. Therefore, this chapter identified the research philosophy as the system perspective. The positivism that objectively justifies and reacquaints the RURB system is argued to be the philosophical change to obtain the system cognition and interactions from conventional empiricism. After the RURB system theory was developed, this chapter argued that a case study based on its theoretical basis should be designed as an exemplar engineering project to verify this theory based on the principle of objective positivism.

Consequently, this chapter coherently explained how the knowledge of RURB was produced in this study, including how the research design was structured, how the research methods and techniques were argued and selected, how the data were collected and analysed and how the research objectives were achieved. The research ethics and originality were also discussed at the end of the chapter. The following Chapter Four will discuss the development process of the RURB system theory whilst Chapters Five and Six will provide the case study and analysis of retrofit benefits and costs.

4. Results of system cognition and interactions of Retrofit of Urban Residential Building

4.1. Introduction

As discussed in Chapter Two, the retrofit of urban residential buildings (RURB) was understood and studied empirically based on previous statistical and project experiences. The current problems of RURB were argued to be the lack of a theory-based RURB definition along with cognition and interactions which have not been formally and systematically analysed.

This chapter aims to find solutions for the first and second research questions raised in the introduction chapter. Therefore, to systematically, identify, analyse, and understand the RURB problems that exist in the present circumstances, it is necessary to have a logical route to describe the whole, realistic RURB system, using an appropriate research method. In this case, the system-thinking approach should be adopted as the core research method to identify both the hierarchical decomposition and systemic connections of the complex RURB system.

Firstly, the system-thinking theories are selected for their ability to provide a rich and reliable description of this complex RURB system. Secondly, the main system elements of RURB are identified with their unique characteristics clarified by adopting the causal layer analysis method to fully describe the nature of the RURB system cognition. Thirdly, to fully understand the RURB system and discover the systemic problems, the connections between system players and system variables are explored based on the theory of causal loop diagrams, which are classified with two main scenarios in which residents' spontaneous retrofit and government-driven retrofit occur.

Afterwards, an ideal cooperative retrofit scenario is presented by uniting the best efforts provided by all system players, which should become the most effective retrofit design principle to support future RURB standard design and policymaking.

4.2. System definition for the retrofitting of urban residential building

4.2.1. Linear or system perspective: what is RURB?

Since there is no clear, official, and objective definition of RURB in the current literature, it can be stated that RURB has been subjectively understood individually from the views of different people. By reviewing the RURB policy, studies and projects, Chapter Two provides a critique of the current conception of RURB as a political task, an engineering work, or an action of a building owner. This interpretivist thinking was argued in section 3.2 and is seen to cause problems of isolation, empiricism, low efficiency, low policy reliability and conflicts between retrofit benefits and costs for the people involved.

The epistemology of interpretivism advocates that the cognition of the complex world is realised by studying the personal experience and views of people within it (Kroeze, 2012). Researchers are encouraged to go deep into real life to understand, explain and reconstruct these concepts and meanings using scientific means and language. From the interpretivist viewpoint on the historical development of RURB, it was subjectively understood with different descriptions and explanations based on different people. In this case, their assumptions can be identified by asking all involved people the question 'What is RURB?'. Responses in the reviewed literature can be deduced as:

> *"Policymaker: RURB is a mandatory political task for current residence stock in the city to achieve national energy conservation targets.*
>
> *Designers and engineers: RURB is a linear design and engineering work. I'm experienced in RURB design and construction, and I know and could provide lots of available materials and techniques to retrofit these houses.*
>
> *Construction works: RURB is a job task to repair, replace, install, or remove relevant building content, retrofit measures or equipment.*
>
> *Scholars: RURB is an action to renovate old residences with new techniques. I'm a professional in RURB techniques and analysis and my knowledge of selecting appropriate retrofit measures is scientific and valuable.*
>
> *Residents: I want to improve my living quality by retrofitting my house, RURB is a process of my own business.*

Material manufacturer: RURB is a personal demand from residents. I produce RURB equipment and materials for the market."

These statements show that the different groups of people involved in RURB have their own subjective understanding of the retrofitting process, as well as their predicted targets and desired retrofit results. In the assumptions behind these answers, RURB is understood linearly as 'a work', 'a task', 'a subject', 'a job', 'a process' or "a mixture of technologies" based on the views of different people. In this linear thinking, people usually see themselves as isolated individuals with their own subjective cognition of the same thing and it is difficult for them to seek cooperation and discover interactions with other individuals (Liebovitch *et al.*, 2020).

As argued from the current literature in Chapter Two, the isolation between different people causes many problems, including the empiricism of RURB design, the low efficiency of retrofit results, the single-building scale of retrofit studies, communication between residents and professionals, conflicts between retrofit benefits and costs and the low reliability of RURB policy. In summary, the diverse subjective answers to 'What is RURB?' from different people can indicate that the RURB is currently understood from a subjective interpretivist standpoint, which is chaotic and has caused problems which have hindered its development. The true and scientific definition and cognition of RURB cannot be comprehensively identified following any of the answers above.

Therefore, this research challenges the rationality and scientific nature of the current interpretivist statement of RURB. From the positivist viewpoint, RURB is an objective existence of the engineering process, which involves cooperation by the different groups of people involved. Instead of asking different people the question 'What is RURB?' to collect different subjective opinions, the positivist logic advocates researchers applying the inductive reasoning method to describe 'the general world' from 'individual objective facts' (Hayes *et al.*, 2010). In this case, different people involved in RURB should be asked the question: 'How will you be benefitted from RURB, and what will it cost?' to collect their retrofit demands, opinions, preferences, and behaviours to provide an objective and comprehensive cognition.

4.2.2. The hypothesis of the RURB system based on inductive reasoning

The thematic analysis method from Boyatzis (1998) is a reliable research method to describe and understand cognition of a fact, common sense or a single system. The thematic analysis uses the concept of unique themes based on qualitative data usually provided from a social survey. The ability of thematic analysis to describe complex social and psychological problems has been discussed and evidenced by many researchers such as Braun and Clarke (2008).

However, as indicated above, it is concerning that RURB may not be clearly understood by applying thematic analysis since the RURB system has diverse opinions and complex interactions between the different groups of people involved. As Tranfield *et al.* (2003) and Haraldsson (2004) stated, a fact with a systematic perspective may have interrelated and contradictory causal links between system variables and system participants for finding a positive proportional or negative inverse relationship. In this case, the nexus dynamics of 'themes' in this system can become too complicated to be clearly understood.

On the other side, the Bayesian notion of the inductive reasoning method of cognitive science has been proven and widely used to explain a system by using an individual phenomenon to establish a general principle (Hayes *et al.*, 2010). The inductive reasoning method is an interpretation method to take a fact, common sense explanation or argument from a certain viewpoint on an individual thing to obtain a wide range of views and a way of understanding general principles and those derived from specific examples (Hayes *et al.*, 2010). As Bayesian theory states, the 'general' in nature and society exists in and through the special 'individual' as objects and phenomena (Skyrms, 2000). Therefore, the general can only be understood after the individuals have been understood.

Inductive reasoning is an inference process from understanding and studying individual things to summarise and generate general laws. The inductive reasoning method advocates that people should summarise and generalise various general principles or principles from individual and special cases when attempting to explain something large and complex. This cognitive order runs through people's interpretation activities while constantly raising the individual to produce general laws (Hayes *et al.*, 2010).

For this research, RURB is an appropriate generalisation with a complex nature. As argued in Chapter Two, RURB currently proceeds with individual projects, but with a linear perspective, which has caused many problems. Therefore, the inductive reasoning method is applied to justify, describe, and explain the ‘general’ as the RURB system definition, based on the ‘individual’ current RURB practices and projects. A RURB hypothesis should hence be established based on the current RURB project reports reviewed, as mentioned in section 2.4. In general, according to the RURB project reports and case studies reviewed, two scenarios can be set based on the ‘driving force’ of RURB as the hypothesis for the RURB system mode:

Mode A: ‘Retrofit driven by the owner of residences’ is the most common, realistic, but wild, uncontrollable, unpredictable, and extremely complicated situation for the majority retrofit of old residential buildings. In this situation, owners of residential buildings spontaneously start to retrofit their houses for many reasons including aspiring to better living quality, more functions, better thermal comfort, changes in the built environment, changes in house planning or asking for a more sustainable and energy-efficient house. Based on the nature of urban residences such as apartment buildings, residents only have ownership of their indoor space, but not the public space and building surfaces.

Under this mode, the impacts of the opinions of residents are significantly amplified as they are the decision-makers and responsible for most of the retrofit design and costs. The residents are isolated, hence the strength of policy support and guidelines from policymakers are weakened in this mode. This condition also points out the most complex factor: the ‘diversity’ of individual residents considering the retrofit of their residential buildings. This diversity factor could be extremely difficult to analyse and solve on a large urban scale.

Mode B: Driven by the government, residential buildings in this mode are going to be retrofitted driven by specific reasons from the local government. The related retrofit construction works are usually covered or supported by governmental strength. From the reviewed documents, the reasons for the retrofit may include reworking a dangerous structure, changes in city planning and the urban renovation of municipal environments. In this case, the top-down administration from the government and policy can achieve great efficiency in solving some of the RURB problems including lack of finance, troubles with retrofit designs and the temporary resettlement of the residents. This Mode B has also been considered as the fundamental situation for the majority of building retrofit studies to avoid the related communication with residents - which was criticised for being too ideal, simple, and linear engineering process.

4.2.3. Justification of ‘RURB is a system’

Since the ‘RURB is a system’ hypothesis has been established, it is necessary to ask the question ‘What is a system?’ to justify the system definition. In this case, the definition of a system by Wright and Meadows (2009) has been widely used in engineering, social sciences and economics:

> *“A system is a set of things—people, cells, molecules or whatever—interconnected in such a way that they produce their own pattern of behaviour over time. The system may be buffeted, constricted, triggered, or driven by outside forces. But the system's response to these forces is characteristic of itself and that response is seldom simple in the real world. When it comes to individuals, companies, cities, or economies, it can be heretical. The system, to a large extent, causes its own behaviour! An outside event may unleash that behaviour, but the same outside event applied to a different system is likely to produce a different result.” (Wright and Meadows, 2009)*

Accordingly, a system should be composed of system entities, interconnections between variables, outside forces, unique characteristics, and system behaviour. The hypothesis of the RURB system and its components should hence be tested and verified to match the above definition of “a system”. From the RURB policy and project documents reviewed in the current literature, the system components involved, and the retrofitting variables can be summarised and listed below:

- By reviewing RURB policy and projects, specific ‘people’ involved in RURB can be identified as follows: policymakers, designers, construction workers, equipment manufacturers, building engineers, scholars of retrofit techniques and the built environment and residents who lived in the old residences. Based on the level of knowledge about RURB, these groups of people can be classified as ‘professionals’, ‘workers’ and ‘residents’ considering their roles in the system. In this case, they can be referred to as system participants of **system entities** in Wright and Meadows (2009) theory.
- During the evaluation of RURB investments and results in the current studies and projects, qualitative and quantitative factors involved in RURB are found to be very diverse and complicated. They can be classified as ‘retrofit benefits’ and ‘retrofit costs’, such as the indoor thermal environment, built functions, energy

consumption, carbon emissions, retrofit designs, retrofit measures, cost and well-being. From the system perspective, they can be regarded as **system variables** in Sterman's theory of system dynamics (Sterman, 2002).

- From the RURB project reports, the driving force of the RURB system can be deduced and hypothetically divided into two modes: resident-driven retrofit and government-driven retrofit. According to Wright and Meadows (2009), 'the system may be buffeted, constricted, triggered or driven by outside forces'. Therefore, RURB has **outside driving forces** applied to its process and development, which also match the definition of a system.

Following the proving logic of inductive reasoning, the RURB system hypothesis is found which contains the necessary system entities and many complex variables, benefits, and problems whose characteristics and complexity satisfy the requirements of both the system definition and system dynamic theories. Based on the Bayesian notion, the probability of 'RURB is a system' reaches a high value while all necessary conditions are proven to exist. Therefore, based on Wright and Meadows (2009), the definition of "a system" for this study - the RURB system hypothesis - can be justified. The definition of the RURB system can be briefly stated as:

> "*RURB is a system operated by a set of groups of people, including professionals, workers, and residents. They are interconnected and cooperate to use their efforts to improve currently unsatisfactory built environments, building performance concerning energy, function and comfort and* the *living quality in the old urban residential buildings.*
>
> *Residents share the ownership of one urban residence and the ability of the individual is limited since residents can only retrofit their own indoor space. Hence the ideal RURB must proceed with communications between different groups of people to increase the retrofit efficiency."*

Yet the characteristics and the interconnections between system components are still complicated and require clarification. From the system perspective, retrofit demands and benefits for energy, indoor comfort and carbon reduction may be completely different from the viewpoints of professionals and residents. This diversity causes barriers when proceeding with the retrofit (Zhang and Wang, 2013), hence this system should be further analysed to provide a comprehensive 'rich description' of the views of different system participants.

4.3. System components

A dynamic system is stated to be composed of system boundaries, system entities and participants, system variables, causal links and feedback (Forrester, 1994). Since the system definition has been justified, in this section, the system boundary of this research is clarified and the system entities i.e., the ‘people’ and ‘variables’ involved are identified as the fundamental components of the system.

4.3.1. System boundary

Following the nature of system dynamic theory (Forrester, 1994) and the practices of Greene and Forrester (1993) and Pan et al. (2018), a complex system such as RURB should be limited within a reasonable system boundary based on the designed research objectives to identify the system entities, system participants and system variables involved and their relationships.

Following the logic of inductive reasoning, the general system boundary of RURB should be obtained from the historical development of RURB policy and projects. Since the reliability of the RURB policy was reviewed and criticised, RURB designers and engineers cannot rely on an official definition and comprehensive BEES. Hence, the use of ‘proper nouns and language’ was confusing and unofficial since terms such as ‘building retrofit’, ‘community renovation’ and ‘indoor refurbishment’ were used during the historical development of RURB. As a result, there were many misleading and mixed concepts e.g., between ‘residence’, ‘existing building’ and ‘community’ or ‘renovation’, ‘function retrofit’, ‘green retrofit’, ‘zero carbon retrofit’ and ‘energy conservation retrofit’, but they all have similar policy content and relevant standards. For example, the ‘green building retrofit to an existing community’ was mentioned in the JGJ/T 425-2017 standard (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2017b), but it changed to ‘renovation for existing buildings’ in GB 55022-2021 but with similar index suggestions.

In this case, the retrofit objectives and research targets of RURB should be clarified beforehand, as studies from Pan et al. (2018) and Dixit et al. (2013) have proven the importance of clarifying a system boundary before researching energy and carbon use in a system. Therefore, it is necessary to use precise words and language before the analysis of system cognition to enable RURB to have its system boundary clearly defined. According to the documents reviewed, there are currently three frequently mentioned confusions used in the field of improving old residences: ‘indoor refurbishment’, ‘community renovation’ and ‘building retrofit’. Based on the theory of setting system boundaries in social research (Luhmann, 2006), a lattice is generated to clearly understand the system entities involved in the three concepts underlying the use of these words.

In the lattice in Figure 4.1, system entities related to building retrofit, community renovation and indoor refurbishment are distributed based on the spatial attributes of a residence from outdoor space, through the external surface of the building, to the indoor content.

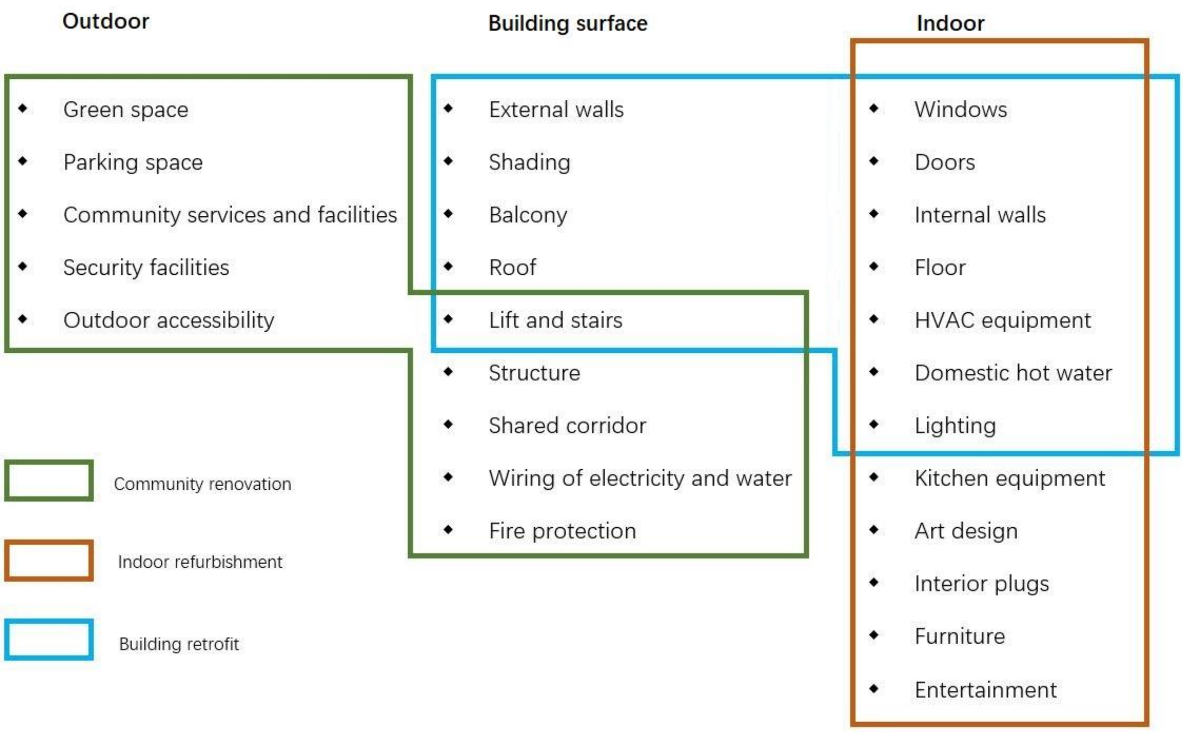


Figure 4.1: System boundaries for the three terms used in relation to RURB

From the reviewed RURB project reports, ‘community renovation’ (as the green frame in Figure 4.1) demonstration projects in China represent the renovation construction works in a zone of residential buildings surrounded by enclosing walls. Community renovation cannot be applied to detached residences and it usually considers outdoor space (such as green space and car parks) and building safety issues (e.g. the reinforcement of the building structure) as the most important aspects of retrofit (China Academy of Building Research, 2018). Under this circumstance, communication and cooperation from residents are usually neglected. Designers and engineers can easily follow the requirements of policymakers and achieve highly efficient construction work. Hence, community renovation can bring improved functionality and well-being to residents from shared public outdoor space, but there are hardly any retrofit benefits for energy conservation and carbon emission reduction.

On the other hand, the concept of 'indoor refurbishment' represents the indoor retrofitting undertaken by the owners of residences, see the brown frame in Figure 4.1. Residents may purchase and introduce more new furniture, electronic equipment and household decorations. In this case, the concept of indoor refurbishment only considers the update and replacement of indoor features to improve thermal comfort, aesthetics and indoor living quality. Potentially, the indoor refurbishment will significantly increase material and energy use with the development of urban residents' income levels.

As a result, in this study, both community renovation and indoor refurbishment cannot fully satisfy the objectives of RURB based on their system boundary - the concept of building retrofit should consider retrofit benefits related to both energy conservation and improvements to the indoor built environment. Therefore, this study develops its RURB system boundary consisting of the building façade and the indoor energy-consuming equipment that provides thermal comfort and which is marked in the blue frame in Figure 4.1. The selected system entities are ubiquitous in every old urban residence and their performance can be seen as variables relevant to both building energy consumption and the indoor built environment.

4.3.2. System participants and system players

After the limitations of the current literature have been discovered, the characteristics of 'people in groups' should be obtained and analysed - who create and make the policy, develop retrofitting technology, and make decisions on retrofitting. They are the core system components in the system. According to the literature from the OECD (Organisation for Economic Co-operation Development, 2001) to explain political and social issues, ‘people’ are the key to social improvement and policy development.

For this RURB study, the research aim is to improve the quality and performance of the built environment of urban society. In this case, it can be seen that aspects of the conventional approaches to building retrofitting policies, designs and studies have met serious challenges, hence the ‘people’ in this system should be identified and their roles clarified. As indicated above in section 4.2, there are six groups of people involved in the RURB system: governmental policymakers, designers and engineers, scholars, residents, material and equipment manufacturers and construction workers. According to the current problems in RURB identified in Chapter Two, the features of the six system participants can be summarised below:

1) RURB policymakers design policy content as building retrofit standards, regulations and government budget plans. As argued, RURB standards are currently very difficult to implement around the nation. The policy contents are weak and unclear with no mandatory rules as there are for new building standards. Policymakers do not have a systematic method to further improve the current situation in RURB policy.

2) Designers and engineers play the role of practitioners during the RURB design and construction. The empirical design and engineering experience is their strength to adroitly select and apply suitable retrofit measures. However, designers currently have no clear and reliable design standards to follow, so they have to set up the retrofit measures on a building-by-building scale, which is very inefficient.

3) RURB scholars have profound knowledge of building retrofit techniques, but most of them are limited to the single-building scale of academic research techniques. So, they work hard to improve the efficiency of very advanced energy conservation technology, but they pay little consideration to local, economic and social issues. As a result, it is difficult for the academic achievements of scholars to be extended into policymaking and to become commonly used in building retrofitting. While scholars are engaged in very advanced building energy research, in reality, policymakers and residents do not have enough awareness of the economic conditions to support applications related to retrofit techniques.

4) Building residents are the final receivers of RURB benefits. They have the least knowledge and experience in building retrofit, but they are the ultimate decision-

makers in the system. Usually, residents are not motivated by professionals to decide to refurbish their indoor environment due to extremely complex factors, such as time, cost, thermal comfort requirements and the troubles caused by retrofit works.

5) Based on the strength of their influence in the system shown in the current literature review, the industrial manufacturers and site workers are more independent of the 'retrofitting' property. The equipment, devices, materials produced or labour provided by these two system participants serve not only for building retrofit but also for new buildings. It means the manufacturers and workers should not be considered core system participants.

Accordingly, the RURB system can be seen as a system structured and operated by four groups of people who are defined as "core system participants". To avoid misleading, the concept of 'system players' who participate in this complex system is raised in this research. These four system players are RURB policymakers, designers and engineers (as one group), scholars and residents.

4.3.3. System variables

As the mandatory components of a system, the RURB system variables shown below are identified and clarified from the reviewed documents based on the defined system boundary and system players:

1) Retrofit measures

   Within the defined system boundary, retrofit measures represent the considered new insulation materials, equipment, devices or functional machines to be introduced through the RURB process. As a system variable, there are different retrofit techniques available for selection by residents or designers each with its price, efficiency, retrofit difficulty and functions. Objectively, retrofit measures are the most important retrofit variables within the RURB design, since they can directly influence the total retrofit benefits and costs.

2) Retrofit benefits

   Retrofit benefits can be extremely varied depending on the application of retrofit measures. From the review of current RURB projects with their result analysis, quantitative retrofit benefits can be reduced energy consumption and reduced energy bills from the retrofitting of building insulation and HVAC equipment. Quantitatively, retrofit benefits are reflected by improvements in indoor thermal comfort, better-built environments, reduced issues of noise and infiltration, and improved safety and accessibility.

3) Retrofit cost issues

Retrofit costs contain four different parts: 1) the investment costs of the retrofit process including materials, insulation, equipment and devices, 2) the labour fees of construction workers, 3) the operating costs of additional equipment and devices and 4) the living costs of a temporary move out of the home during retrofitting works. To policymakers and residents, the retrofit cost issues can be addressed through the concept of an 'affordable allowance' based on their retrofit desires and economic circumstances.

Potentially, retrofit cost issues might be the most important negative factor influencing the RURB design and decision-making. However, they can be reduced from the cost benefits of retrofit measures through energy conservation to achieve lower energy bills and by governmental subsidy. Therefore, the retrofit cost issue is a complicated system variable associated with many interactions inside and between other variables.

4) Troubles from retrofit engineering work

Unavoidably, retrofitting construction works will cause trouble for the current residents. For example, the replacement of heavy indoor equipment and devices may cause troubles from the temporarily disabled functions of equipment, its movement and installation. Meanwhile, the insulation retrofitting of the building's external façade, new lift installation and replacement of external windows will bring comparatively long-term troubles of noise and accessibility. This system variable is highly related to both the selection of retrofit measures and the professional ability and work efficiency of RURB engineers.

5) Energy and carbon problems, subsidies and support

As indicated in section 2.2, reducing energy consumption and carbon emissions are the political objectives and achievements of government policymakers.

Governmental subsidies and support are the means to motivate the residents to achieve the political tasks involved in RURB more quickly and effectively. Subsidy and support can significantly encourage RURB residents to make decisions on retrofitting by reducing the economic pressure in three ways: 1) providing direct financial support, 2) partly paying the material and equipment manufacturers to raise discounts and 3) even covering all the investment, design and construction works of RURB. Based on its nature, quantitative subsidy and support is highly dependent on the local economy and tax levels (Potůček, 2018), as well as the local government's emphasis on the benefits of RURB.

6) Local conditions

The location of RURB can allow significantly diverse local conditions to influence the retrofit benefits, costs and efficiency. Local conditions include both physical and social factors, such as climate and weather conditions, occupancy behaviours and culture, residents' preferences for retrofit measures, the physical building conditions, historical development and economic level. Based on positivist theory, to comprehensively understand a system with all its objective aspects, the local conditions can be identified as another complex system variable. The importance of increasing RURB efficiency is argued as an insight in Chapter Two since the local conditions have usually been neglected in RURB studies and designs.

4.4. System Player Analysis (SPA)

Once the system definition and the system components including the system boundary, system players and system variables have been clarified, it is necessary to deeply analyse the knowledge of this system to acquire its system cognition. Since the inductive reasoning approach may not be suitable for such a complex system, in this section, an adapted approach based on the causal layered analysis method will be developed by considering system players as the core system entities and driving forces.

4.4.1. Causal Layered Analysis (CLA)

To obtain a rich description of the cognition of a complex system, Causal Layered Analysis (CLA) is a structural theory developed by Inayatullah (1998) to review a long historical record and identify possible predictions for the future (Riedy, 2008). Inayatullah (1998) developed CLA as a theory that *'seeks to integrate empiricist,* *interpretive, critical and action learning modes of knowing'*. Inspired by post-structural and critical thought from groups of involved participants, the concept of a four-level layer was defined by Inayatullah, including 1) the litany; 2) the level concerned with systemic causes; 3) the worldview and 4) the myth and metaphor.

In CLA thinking, the cognition of knowing should be summarised based on the qualitative discussion from workshops with system participants. As evidence, Riedy (2008) proved that CLA can be used to guide theoretical research in a more practice-oriented context, by proceeding with a workshop based on action learning. Meanwhile, CLA has proven highly successful in addressing deep cultural or social commitments, worldviews, myths and hidden metaphors that help people shape the objective facts for interpreting 'the world' or 'a system' (S. Kim *et al.*, 2021). Considering the history of RURB development was argued and criticised as being project-based empiricism, applying CLA in the cognition of RURB is an appropriate method of developing a layered understanding of reality (as the concept of 'world' in CLA) which provides a basis for information management, the convergence of divergent opinions from participants and assumptions about the future.

However, the CLA method has its limitations when representing the psychological situation of individuals, such as personal values, abilities, experiences and consciousness. CLA focuses on 'collective futures' involving system participants from workshops, but the workshops usually have a too small amount of people attending to be representative (Riedy, 2008). As criticised by Riedy (2008), Inayatullah's CLA should be specially adapted both for its layer definitions and data collection methods when researchers attempt to understand a complex system structured by practice-oriented content. In this case, Riedy (2008) developed an interpretation of CLA with three integral concepts: quadrants, developmental levels and developmental lines to better understand the information from individuals.

Meanwhile, the SWOT method could also be seen as an adapted CLA approach with a matrix relationship based on four quadrants: strengths, weaknesses, opportunities and threats - to replace CLA's four layers - to find possible strategies for enterprise development (Jackson *et al.*, 2003). Therefore, it is possible and necessary to adapt Inayatullah's CLA theory based on the research purpose, system environment and system complexity of this RURB study.

4.4.2. Adopted causal layered analysis: System Player Analysis

Among the themes identified in current RURB policy and projects by the document scan, the concept of 'people in groups' can be regarded as system participants or, more clearly, 'players'. Four groups of people have their unique roles: to create and make the policy, develop RURB technology, make the decision to retrofit, and proceed to the retrofit design and engineering works. They are defined as the dominant system variables in the RURB system and each of them has its inner layers with individual characteristics.

As argued by Riedy (2008), the layers in CLA may confuse quadrants, developmental levels and lines between layer relationships, which shows that CLA meets the limitation of accurately examining the psychological aspects of individuals. However, the diverse economic levels, personal experiences and preferences are very important for the local advantages of RURB development - individual factors are crucial in collective decision-making since '*reality is composed of parts, which are also wholes of other parts*' (Riedy, 2008). Additionally, CLA usually collects qualitative data from workshops in which the lack of articulation makes it difficult for the CLA to reduce participant bias. Therefore, CLA has to be adapted with its concept of 'participant' changed to accommodate two types: 'professionals' and 'residents', since most of the residents are not professionals, but all professionals are also residents in reality. Correspondingly, the four-level layers: the litany, systemic causes, worldview and myth/metaphor identified by Inayatullah (1998) are adapted to form five layers for system participants: roles, outputs, issues, demands and features (ROIDF) of RURB:

1) **Roles and outputs**: The concept of "groups of people" includes the unique role of 'players' and the practical outputs of RURB development as fundamental properties found in the SPA characteristics. From the descriptive themes identified from the document scan ('the litany' of CLA), "roles" can be briefly defined as an "initiator, executor, developer and decision-maker" with "outputs" including retrofit design standards, retrofit construction work, techniques used in retrofit measures and the retrofit benefits. These are matched with policymakers, workers, scholars and residents.

2) **Issues and demands**: Similar to the concept of "system causes" from individuals in CLA, the "issues" and "demands" of RURB are extremely diverse and complex

given the changing views of system participants. As a shallow causal relationship, the differences in the benefits expected from RURB (as the worldview layer of CLA) by the four system players are caused by divergent preferences, which further cause many individual problems for the retrofit cost, the selection of retrofit measures and the requirements expected to result from the retrofit.

3) **Features**: Inferred from Inayatullah (1998), the CLA's "myth and metaphor" layer applied to their collective future can help participants to outline how people interpret their world, but it has problems in representing the values and impacts of individuals. Therefore, as an adapted theory specific to the RURB system's condition, SPA regards the individual features of the above four layers as important.

In summary, this study adapts CLA to system player analysis (SPA) which identifies that RURB is playing (or operating) in a system using specific groups of participants acting as policymakers, designers & engineers, scholars and residents. Based on the description of clarifying involved "system entities" from Haraldsson (2004), the four main players can be classified into two groups: 1) "professionals" including RURB policymakers, designers, engineers and scholars, and 2) the "residents" living in the building. Following the definition of the 'system players' concept, it is important to discover and discuss their characteristics to completely understand the RURB system. The ROIDF characteristics of each system player are defined according to five important factors based on the nature of the RURB development, as in Figure 4.2.

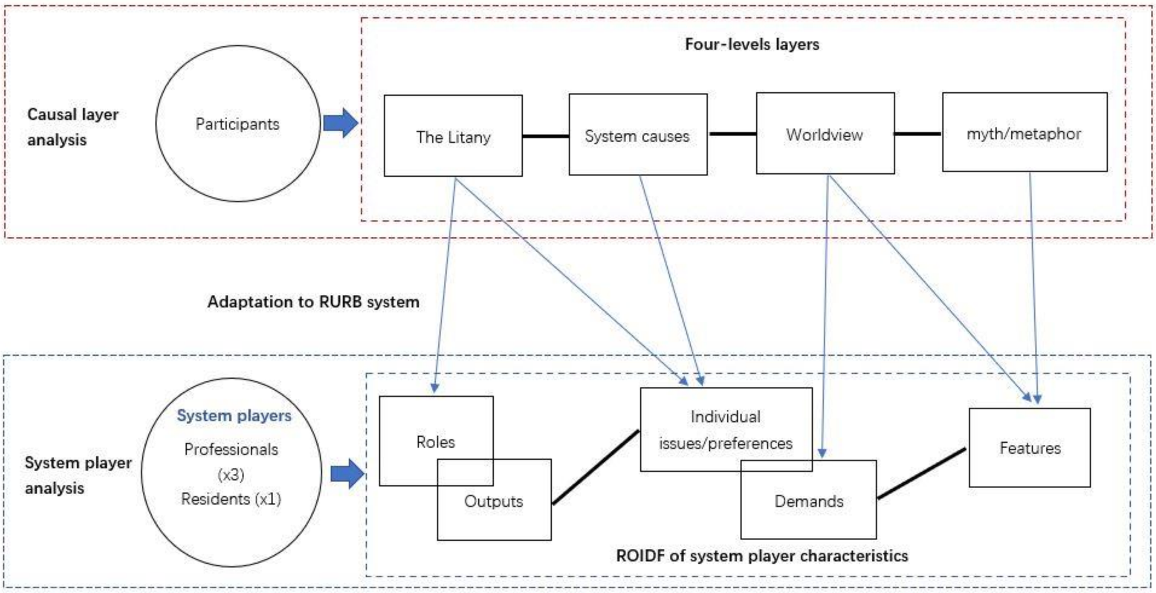


Figure 4.2: Adapting CLA to system player analysis of RURB

4.5. Result of interviews

In this section, the results collected from the semi-structured interviews are analysed according to the system players of professionals:

1) Frequently mentioned keywords

After the 12 professional people interviewed with the conversation results summarised and analysed from records and notes, there is an overall figure showing the frequency of the important and popular keywords mentioned by more than 80% of interviewees (10 of 12), shown below as Figure 4.3.

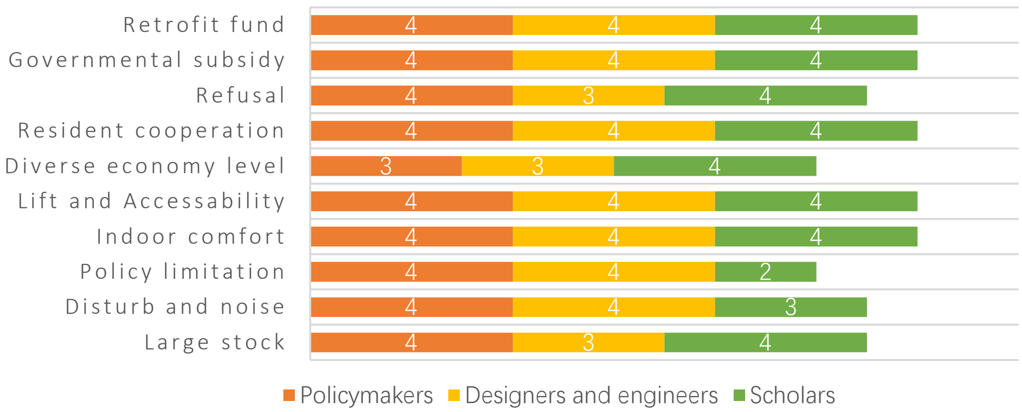


Figure 4.3: Frequently mentioned keywords and the number of their interviewees

This figure provides a clear overall picture of the most important 10 components of the modern RURB, as the retrofit fund, resident cooperation, indoor comfort, lift & accessibility, governmental subsidy, economy level, refusal of particular residents, limitation of current RURB policy, disturb and noise of retrofit construction work, and a large amount of current residential building stock in China. From the review results, these keywords are highlighted by the majority of RURB policymakers, designers, engineers, and scholars, and should have the highest priority for future RURB development. Later, the individual interview results are summarised and discussed in the below section, based on their RURB role.

2) Policymakers

The current retrofit policy is weak: as people who design and manage the RURB policy themselves, all 4 interviewed policymakers together with all other interviewees admitted more or less that the current RURB policy is very weak and limited compared to the developed new building regulation and public building standards. Person A, B and C stated the development of the RURB policy is very slow because of the complicated nature of residential buildings such as differential built environment, built age, economy level and education level of residents. They said it is incredibly difficult to design a standard for the general use of RURB, and the possible approach is to establish a different retrofit level, and then find the suitable one for each individual old residence rather than one standard for all cases.

Governmental support is mandatory but limited: although the retrofit investment cost is shown as one of the most highlighted keywords which have been mentioned by all 12 people, the governmental subsidy for RURB, however, is a very related factor explained by policymakers on the view of the government. Person A, C and D believe that government cannot afford all the retrofit costs, but some essential safety retrofit measures including quakeproof, fire protection and wire routing. For the other retrofit measures as energy and comfort, the government must find a more appropriate way to scientifically use the limited amount of governmental subsidy. For example, currently, the national government provide some discount on energy-saving HVAC equipment and some financial support for new lift installation on old residences.

Average comfort and energy use are low: to discuss the current average building condition of old residences, persons A and C said the overall living environment quality in China is much lower than in developed countries. It means that many residents are still not living inside the thermal comfort zone or have a good living environment, so the average energy consumption is low - energy saving may not be the priority during the RURB policy design. Residents care much more about accessibility, safety and a better environment and hope for more lifts, parking spaces, clean and beautiful views, and larger room space. However, persons A, B and D also stated that the government must think further as Chinese people will pursue better living quality and thermal comfort in future, together with the rapid development of the economy and urbanization. Especially, person B mentioned the COVID-19 pandemic raises a new phenomenon that people will stay in their homes for much longer compared to normal life to reduce the risk of infection. Therefore, it will become a common trend faster that people who work at home will ask for a more comfortable and functional home to increase productivity just like the office building.

Hard to get cooperation from residents: all four policymakers admitted that it is extremely difficult to acquire cooperation from all residents. From their experience, only one refusal may cause delay or cancellation of the whole building retrofit work, even if all the cost is paid by the government. This kind of stubborn resident insists to deny any changes and improvements to his owned home no matter the cost, or they may refuse the lift installation due to possible noise issues. This brings a serious problem for future RURB policy design as it is impossible to force residents to accept the retrofit with mandatory building regulation, but communication and persuasion might be the only appropriate way – which is a social issue and cannot be easily quantified during policymaking.

3) Designers and engineers

Empiricism: all four designers interviewed admitted that the RURB design is much more difficult than the new building design. They stated that new building designs have been well developed which has become standardization as an assembly line from bidding to check out. For RURB, however, designers are working with extremely low efficiency, as they must use their personal experience to select and design the retrofit measures. Since there is no reliable design code and standards, persons F, G and H complained that a wide variety of individual design ideas could be found in the finished RURB demonstration projects. As a result, it is very difficult to evaluate their retrofit effects and to make references for future retrofit designs, which means that designers and engineers must do single building-by-building and repeat all the steps from the beforehand survey to communicate with residents.

Limited funds: as mentioned by persons E, G and H, the total budget provided by residents or the local community is usually very limited. They mentioned the current policy of RURB to select some residential communities as demonstration projects, so they can receive the subsidy, professional designers and construction teams supported directly by the government. However, there are a large amount of old residential communities that have not been chosen but required urgent retrofit – they have very limited funds provided by residents to designers and engineers. From the view of designers, it could be very regrettable that they should have achieved better-retrofitted results due to the lack of financial support, although they have the abilities of design and engineering.

Individual satisfaction: three designers admitted that the final retrofit plans after long discussions and many revisions still could not be accepted by all residents in the same old residential building. They complained that there were always a small group of residents who unreasonably refuse the revised retrofit plan, although the current living condition is extremely bad, dirty, and dangerous. However, it is very difficult and inefficient for designers and engineers themselves to take part in communication between residents and property companies. It brings a message that there should be the government's responsibility to develop policies or support proper education and propaganda to persuade some 'stubborn' residents, and to let them understand the benefits of RURB.

4) Scholars

Window: all four interviewed scholars frequently mentioned the external window as the most important keyword. Persons I, J and K excitingly described the importance of window retrofit for old residences, as they stated that it is technically the most effective component for energy conservation and living quality improvement. Scholars believe that it is possible to achieve more than 30% energy consumption for heating and cooling by only simply replacing single-layer glazing with low-E two- or three-layer glazing with insulated frames. Furthermore, all four scholars mentioned that the replacement of windows is much cheaper, easier, and faster rather than the retrofit of external walls, but it has the highest effect in both energy saving and reduced indoor noise issues. They believe that the window should be the priority during the consideration of RURB design and policymaking.

Technical problems: positively, all four scholars mentioned that there are no technical problems for RURB design and engineering. The current technology and construction teams in China are very professional and experienced to retrofit old buildings with modern measures. Persons I and L stated that the retrofit measures are similar to goods displayed in the supermarket which are developed long ago and waiting for selection, but the problems are more about not enough funds and refusal from residents. It means that academically, studies of communication and arousal of social issues are research direction in future rather than technologies, as the correct purpose is to let residents retrofit their homes more cooperatively and spontaneously.

Motivation to residents: all four scholars stated that the most possible solution for retrofit costs should be to attract residents to partly pay for retrofit voluntarily. However, persons I, J, and L mentioned that residents have little interest in energy saving, environmental protection, and low-carbon career. Three scholars stated that even themselves will not be attracted and pay for the retrofit cost based on these general, national, and global objectives. Residents only care about their personal living quality and thermal comfort, which is egoistic, but very realistic. It brings a warning that the conventional reputation concepts used in green building policy are not suitable for RURB propaganda, as it may even incur antipathy to residents.

Neglected details: not only the common problems mentioned by other interviewees, but scholars also have discussed many details and minor retrofit aspects which are usually neglected. For external building façade except for windows and walls, scholars I, K and L mentioned the roof should also be a very important retrofit component. They stated that the majority of old residences have plain roofs with rain leakage and thermal storage problems. Surface water resistance or flat-to-slope retrofit should be applied to reduce mildew and summer overheating issues. Likewise, scholars stated that reflective coating and external shading designs can be very economical retrofit measures on the HSCW zone, as traditional insulation retrofit on the external wall are very expensive but have less effectiveness in southern China due to the high value of solar radiation and warmer weather in winter compared to northern China.

In summary, the interview result provided valuable knowledge on the view of three different professional players of the RURB system. The main and critical problems are revealed as no powerful policy, lack of retrofit funds, limitation of governmental subsidy, refusal from local residents, and current low efficiency of retrofit design and engineering.

Additionally, as the open questions Q10 to 12 asked about their personal experience and hypothesis when standing on the side of the resident during the retrofit, they provided many useful ideas and opinions to help the later questionnaire design section. For example, 8 of 12 people prefer to have a comprehensive retrofit around 2-3 months and residents must temporarily leave the residence, while 2 interviewees prefer to purchase and move to a new home as they mentioned they cannot stand the dirty, old, and inconvenient outdoor environment no matter how luxury they retrofit their own indoor rooms. It shows an interesting fact that although interviewees are very professional and experienced in RURB, some of them may still have an inactive attitude about retrofitting their own homes.

4.6. Results of the questionnaire survey

In this section, the results collected from the questionnaire survey are analysed according to the system player of residents:

1) Building conditions

Questions 1, 2, 3 and 5 collected answers to clarify the properties of old residences. Basic physical building information of their referenced old residences from residents is shown below in Table 4.1.

Table 4.1: Basic information collected to identify old residences

No.	Question	Option	Sample	Proportion
1	Area	< 40 m2	65	6.4%
		41-80 m2	427	41.8%
		81-120 m2	413	40.5%
		121-160 m2	91	8.9%
		> 160 m2	25	2.4%
2	Occupant number	1	25	2.4%
		2	122	11.9%
		3	517	50.6%
		4	260	25.5%
		> 5	97	9.5%
3	Building type	Bungalow	78	26.7%
		2-6 floors	504	73.3%
		7-12 floors	259	25.4%
		> 12 floors	143	14.0%
		Detached house	37	3.6%
5	Built age	< 1980	66	6.5%
		1980 - 1995	292	28.6%
		1996 – 2010	399	39.1%
		2011 - 2015	109	10.7%
		> 2016	41	4.0%
		Don't know	114	11.2%

Results of questions 1 and 2 show the total indoor area and occupant number, as in Figure 4.4. It proves that small-sized housing is the most common type for 42% of old residences only having areas of 41 to 80 m^2, and 41% of people have their old residences with larger areas of 81 to 120 m^2. From a side view, these results show the average economic level and building conditions are relatively bad and residents may be not prosperous to afford luxury retrofit measures.

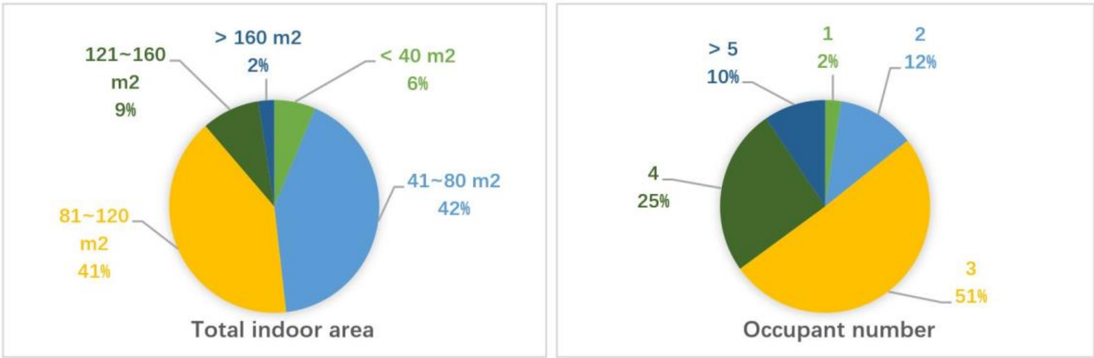
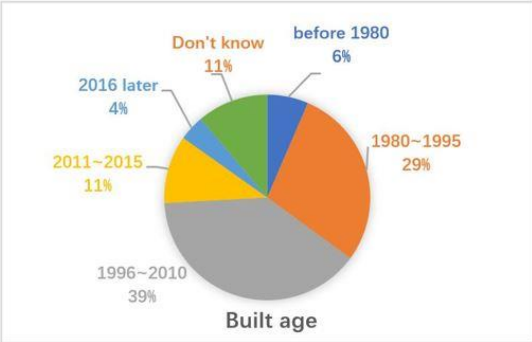


Figure 4.4: Result of indoor area number and occupant number of old residences

Figure 4.4 shows the result of questions 3 and 4 of the built age and building type of old residences. It reveals that 29% of old residences were built between 1980 to 1995, while 39% majority of old residences were built between 1996 to 2010. In the HSCW zone, 2001 was the year when the first energy conservation design standard was issued as JGJ 134 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2001), but this standard was an undeveloped code without comprehensive rules of building characteristics. Since there was a milestone update (Han et al., 2021) of the JGJ 134 standard issued in 2010 with many more mandatory rules (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2010b), the result of the question 3 proves that all residential buildings in HSCW zone built before 2010 could be considered as ‘old residences’ for RURB. Furthermore, typical building types of old residences are also revealed by question 4, as 2 to 6 floors apartment count for 49%, and 7 – 12 low-tower apartments for 25%. It also verified the reality that nearly half of the less-than-7 floors old residences have no lift and accessibility design following the old design code of residential buildings GB 50096-2011 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2012a).



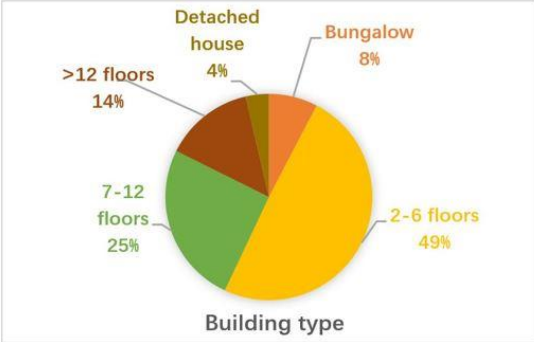


Figure 4.5: Result of built age and building type of old residences

Results from questions 4 and 6 provide average lived time and lived time before the last comprehensive retrofit, as in Table 4.2 and Figure 4.5. It shows that surveyed residents have their answers provided under very diverse conditions of current old residences. As result shows that the majority 38.4% of residents have lived in the old residence for more than 10 years while up to 38.2% of old residences have not been retrofitted for more than 10 years, which may bring a sense of responsibility to RURB policymakers that the potential number of residents who suffer in very poor building conditions is very high and have the largest proportion of the population in the society.

Table 4.2: Years lived in old residences and years between the last time retrofit

No.	Question	Option	Sample	Proportion
4	Year lived	< 1 year	35	3.4%
		1 – 3 years	171	16.7%
		4 – 6 years	227	22.2%
		7 – 9 years	196	19.2%
		> 10 years	392	38.4%
6	The year between the last time comprehensive retrofit	< 1 year	28	2.7%
		1 – 3 years	127	12.4%
		4 – 6 years	213	20.9%
		7 – 9 years	138	13.5%
		> 10 years	214	21.0%
		Never retrofitted	176	17.2%
		Don't know	125	12.2%

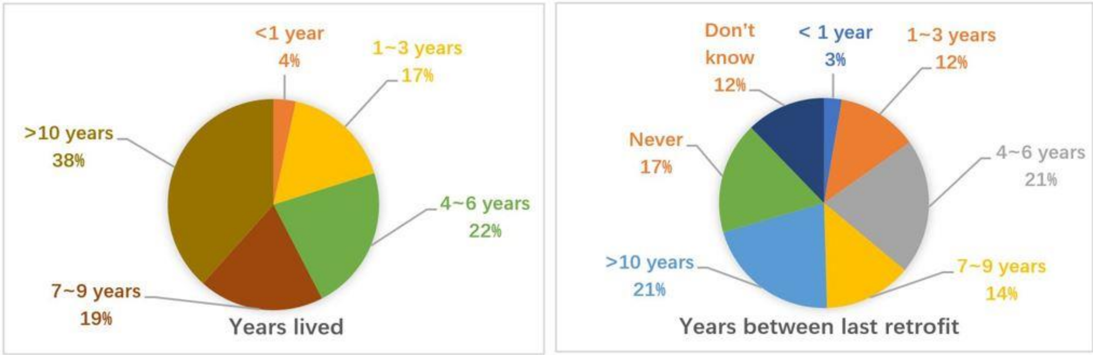


Figure 4.6: Result of years lived and years between the last retrofit from residents

2) Thermal comfort

Questions 7 and 9 aim to understand the current thermal feeling in summer from residents who live in old residences without any cooling equipment. As excepted, over 64% of residents have uncomfortable and even very uncomfortable thermal comfort feelings. This result provides the potential for thermal comfort improvement by retrofitting thermal-related measures of old residences. Also, as shown below, the most popular cooling equipment in the HSCW climate zone is split air conditioners, which are accepted by 80.2% of surveyed residents. This preferred choice for future cooling equipment shows the realistic situation of increasing demand for thermal comfort in summer - fans and ventilation may no longer satisfy the local residents, and the central cooling system might be too expensive.

The condition of thermal comfort in winter is much more complicated in the HSCW zone. Although the average outdoor temperature in winter is not as cold as in northern China, the poor building façade and lack of heating devices have still caused many residents to suffer from an uncomfortable cold indoor environment (Guo et al., 2015). The result of question 8 proves that nearly half of the surveyed residents 49.6% have very bad thermal comfort feelings in winter when they live in old residences without powerful heating equipment.

As policymaker interviewees indicated, there is an increased social voice of more winter heating from people living in southern China. In recent years, people of southern China start to admire the similar central heating system as people living in northern China already have. However, the central heating system has been technically calculated, criticised, and proven as a very inefficient approach if applied in south China, as it is very expensive and the winter climate of the HSCW zone is more moderate compared to severe cold and cold zones (Tsinghua University Building Energy Research Center, 2013). Therefore, split heating equipment should be the appropriate approach to increase the winter indoor thermal comfort in the HSCW zone, as the result of multi-choice question 10 shows the preferred future heating devices for old residences. It shows that residents who live in old residences in the HSCW zone prefer to have economical heating devices such as split air conditioners (48.3%) and electric heaters (40.5%) rather than expensive floor heating and gas radiators.

3) Energy

In Table 4.3, the results of questions 11 and 12 show the differences in residents' economic feelings about the energy bills for summer cooling and winter heating in the HSCW zone. They shared a similar result as interviews that the average level of thermal comfort is low in China as the majority of 54.3% and 46.0% residents have acceptable feelings about energy bills during extremely uncomfortable seasons. There are still 36.5% and 38.6% of residents who have an expensive feeling about their current energy bill, which proves that the future retrofit measures on the external façade can significantly reduce the burden of the energy bills of residents living in old residences for improved well-being.

Table 4.3: Feelings of the energy bill and update of heating and cooling energy equipment

No.	Question	Option	Sample	Proportion
11	The current feeling of the energy bill for summer cooling	Very expensive	46	4.5%
		Expensive	373	36.5%
		Acceptable	554	54.3%
		Cheap	35	3.4%
		Very cheap	7	0.7%
		Don't know	6	0.6%
12	The current feeling of the energy bill for winter heating	Very expensive	77	7.5%
		Expensive	394	38.6%
		Acceptable	470	46.0%
		Cheap	49	4.8%
		Very cheap	3	0.3%
		Don't know	28	2.7%
13	The desire of introducing new heating and cooling equipment	Yes	579	56.7%
		Will consider	36	3.5%

No.	Question	Option	Sample	Proportion
	during retrofit	No	340	33.3%
		Only if the old devices are broken	66	6.5%
14	The important factors during the consideration of selecting a new heating and cooling device (choose two)	Price	553	54.2%
		Energy efficiency	851	83.3%
		Looks and design	114	11.2%
		Easy to install	171	16.7%
		Long lifetime	285	27.9%
15	To increase the frequency of HVAC equipment usage after retrofit (even if it will increase energy bill)	Yes	560	54.8%
		Probably	443	43.4%
		No	18	1.8%
16	To retrofit building façade to reduce the energy bill by increasing HVAC equipment effectiveness (Unit: RMB yuan)	Yes	573	56.1%
		Probably	406	39.8%
		No	42	4.1%

Questions 13 to 16 are integrated questions designed to collect the preference and behaviour about new energy equipment after the retrofit. The results of question 13 show a large proportion of residents 39.8% are still feeling satisfied with the current HVAC equipment and have no desire to introduce new heating and cooling equipment during the retrofit. This result may bring concern about the traditional RURB policy of providing a discount on new, energy-efficient heating and cooling devices. Unexpected by interviewed scholars, the result of question 14 shows that energy efficiency is the most important factor for residents when they are selecting a new heating and cooling equipment, with much more people 83.3% compared to the thoughts from professionals as the price is the most concern (54.2%). Combined with questions 15 and 16, they prove that the majority of residents have already received the influence of development in education and the economy. People have started to pursue better indoor thermal comfort, while they worry about the energy efficiency of energy equipment to reduce their operation energy bill, but not the initial price of equipment.

4) Cost

Questions 17 to 22 ask residents about their concept and affordability of retrofit economy cost, and their preference of retrofit measure if they will have comprehensive or minor retrofit work costs paid by themselves, as in Table 4.4. Surprisingly, although limitation retrofit fund is one of the most frequently mentioned keywords in the interview, question 17 shows that only 28.7% of residents agree that money cost is the biggest problem during the retrofit. Linked with the affordable allowance result of question 22, there are 41.4% of HSCW residents who live in old residences can afford 50k to 100k CNY, and 30.1% of residents can pay for higher than 100k. It proves that residents have some ability to afford the retrofit expenses, and money cost may not be the most difficult problem as mentioned by interviewees.

Table 4.4: Retrofit money cost, allowance, and preference of retrofit measures

No.	Question	Option	Sample	Proportion
17	Residents' opinion that if they feel the money cost is the biggest problem	Yes	293	28.7%
		No	58	5.7%
		Only partly	670	65.6%
18	Preferred retrofit measures for self-paid comprehensive retrofit (multi-choice)	External wall	517	50.6%
		Window	559	54.8%
		External door	414	40.5%
		Floors	454	44.5%
		Roof	568	55.6%
		Heating equipment	665	65.1%
		Cooling equipment	663	64.9%
		Shading	315	30.9%
		Mechanical ventilation	424	41.5%
19	Preferred retrofit measures for self-paid minor retrofit (multi-choice)	Window	564	55.2%
		Internal doors	467	45.7%
		Heating equipment	624	61.1%
		Cooling equipment	648	63.5%
		Shading	352	34.5%
		Mechanical ventilation	347	34.0%
20	Preference for residents to get from the government during the retrofit	External wall retrofit led by the governmental team	225	22.0%
		Discount on heating and cooling equipment	218	21.4%
		Step tariff for energy price	136	13.3%
		Professional construction team provided by the government	203	19.9%
		The indoor design team provided by the government	239	23.4%
21	The most expensive retrofit measure for residents	Buy new HVAC equipment	402	39.4%
		Buy new furniture	61	6.0%
		Buy new electronic devices	87	8.5%
		Construction work	231	22.6%
		Building material	404	39.6%

No.	Question	Option	Sample	Proportion
		Door and windows	4	0.4%
		Living costs due to temporary move out	132	12.9%
22	Affordable range from residents to retrofitting an old residence (Unit: RMB yuan)	< 50 k	291	28.5%
		50 k – 100 k	423	41.4%
		100 k – 200 k	227	22.2%
		200 k – 500 k	71	7.0%
		500 k – 1000 k	6	0.6%
		> 1000 k	3	0.3%

In addition, questions 23 to 25 ask about the time cost issues for retrofit construction work. The results of Table 4.5 clarify the time cost issue is much more acceptable compared to the economic cost of question 17. It provides a very clear allowance range of time cost due to the retrofit construction work, as less than 2 months. It brings realistic information for retrofit designers when planning and selecting the retrofit measures – the difficult retrofit such as external walls should be carefully considered. Furthermore, question 25 raised an interesting and positive signal to RURB policymakers - 44.6% of residents who live in old residences already have plans to retrofit their homes spontaneously even without governmental support.

Table 4.5: Retrofit time cost and time allowance

No.	Question	Option	Sample	Proportion
23	Residents' opinion that if they feel the time cost is the biggest problem	Yes	327	32.0%
		No	639	62.6%
		Only partly	55	5.4%
24	The maximum allowance of time for retrofit construction work	< 1 week	62	6.1%
		1 – 3 weeks	262	25.7%
		1 – 2 months	480	47.0%
		2 – 3 months	181	17.7%
		> 3 months	36	3.5%
25	Comprehensive retrofit plan for this old residence within 3 years	Yes	455	44.6%
		No	215	21.1%
		Not sure	351	34.4%

5) The desire for retrofit, and resident coordination

The result of question 26 shows that the comprehensive retrofit is still overwhelmingly more popular among residents, even residents must leave their homes and find other places to live for weeks and months, as Figure 4.7. Only 27% of residents will insist on not temporarily leaving their homes and only having minor refurbishments. This result also brings a linkage with question 24 of the allowance of temporary leave, so the RURB policymakers and designers should carefully choose the retrofit measures to avoid causing longer disturbing troubles.

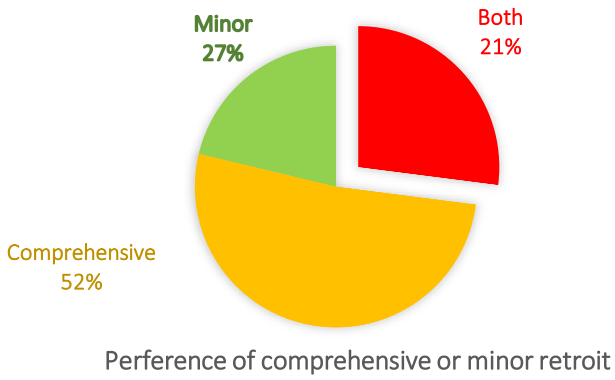


Figure 4.7: Result of preferred retrofit mode (minor, comprehensive, or both)

For retrofit measures related to indoor environments, questions 27 to 29 ask residents if they have a strong desire to retrofit walls, roofs, floors, windows, doors, and update HVAC equipment, in Table 4.6. From the result shown in the table below, there are 67.1% of residents have a strong desire to have their walls, roofs and floors retrofitted, while 23.8% answered for not sure, and only 9.1% of residents insist on no retrofit. Meanwhile, there is a much higher proportion of 80.7% and 80.8% of residents who want to have their windows and doors retrofitted and old HVAC replaced with new equipment with refusal answers of only 7.9% and 6.5%. This result partly verifies the interview results from designers and scholars – the window and HVAC equipment should be the most important component which should be the top priority during the consideration and policymaking of RURB.

Table 4.6: The retrofit desire of building façade and HVAC equipment

No.	Desired retrofit measure	Sample asked for a yes	Proportion
27	Walls, roofs, floors	685	67.1%
28	Windows, doors	824	80.7%
29	New HVAC equipment	825	80.8%

Moreover, as one of the most frequently mentioned keywords, question 30 collects the answer about resident coordination if they want to cooperate and accept the disturbance from retrofit construction work caused by government-led retrofit on external building façade. Surprisingly, although all interviewees stated that cooperation is one of the most difficult social issues during the retrofit, the questionnaire result as Figure 4.8 shows that 93.8% of the majority of residents have the awareness and are still happy to cooperate, and only 1.4% residents resolutely oppose any retrofit works to their home. This breaks the conventional myth of 'residents usually refuse to retrofit their home' from interview results, and it brings the good news that communication and persuasion could be faster and easier in future RURB progress.

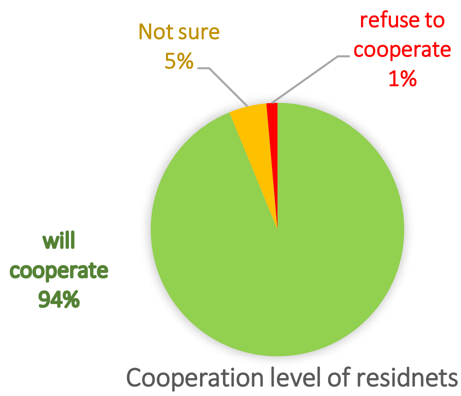


Figure 4.8: Cooperation level collected from residents

6) Knowledge of retrofit

Questions 31 to 33 aim to acquire the knowledge level of a retrofit from surveyed residents. the result of Table 4.7 shows that the majority of surveyed residents have the right to retrofit decision-making, while there is only 15.8% of residents have no experience and knowledge about building retrofit, indoor design, and HVAC engineering. It shows a positive signal to RURB professionals that communication and persuasion could be easier while residents have higher education levels and knowledge reserves for retrofit measures and effects.

Table 4.7: Retrofit knowledge reserve of residents

No.	Question	Option	Sample	Proportion
31	Right or influence to make the retrofit decision of surveyed residents	Yes	701	68.7%
		No	115	11.3%
		Not sure	205	20.1%
32	Knowledge level of building retrofit, indoor design, and HVAC engineering of surveyed residents	Basic knowledge	219	21.4%
		Professional knowledge	114	11.2%
		Only retrofit experience	527	51.6%
		None	161	15.8%
33	RURB design or policymaking experience of residents	Yes	273	26.7%
		No	748	73.3%

Finally, question 34 is summative and asks for the overall preference of retrofit aspects. It is a multi-choices question that residents imagine the prospective picture of their retrofitted home and select their preferred changes and improvements.

From the result in Figure 4.9, the data marked as green are within the proposed RURB system boundary. It shows that improvement of indoor thermal comfort still has the top priority during the consideration of retrofit, while less noise and infiltration, reduced energy bills, and better indoor air quality are also important. Interestingly, the result also verifies the unique thought provided by scholars – common residents have less interest and awareness in environmental protection and low-carbon careers.

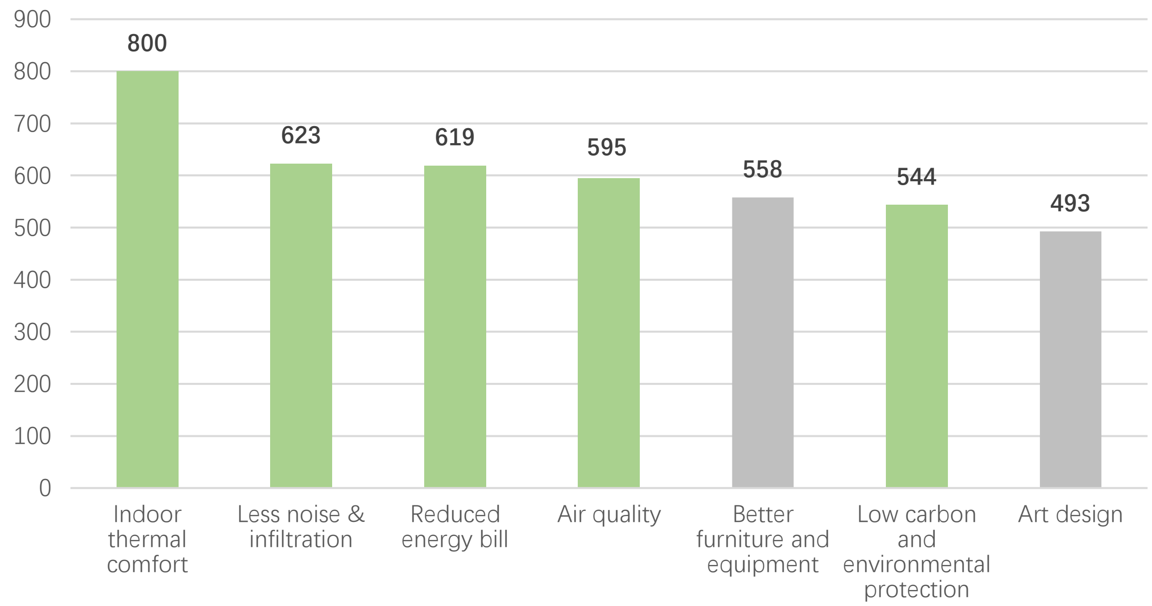


Figure 4.9: Important aspects of a future retrofit from the view of residents

4.7. Results of system cognition

As evidenced by the above survey results, the SPA model of RURB can be clarified using the "four groups of people" involved as the main system players. Their individual Roles, Outputs, Issues, Demands, and Features (ROIDF) are revealed as a matrix relationship in Table 4.8, based on a theoretical basis similar to the concept of system layers from CLA theory.

Table 4.8: Analysis of ROIDF for RURB system players in China

System Player	Policymakers	Designers & Engineers	Scholars	Residents
Roles	◆ Initiator ◆ Enforcer ◆ Proponent	◆ Executor ◆ Planner & Worker	◆ Developer of techniques ◆ Adviser	◆ Decision maker ◆ Payer ◆ Benefits receiver
Outputs	◆ RURB policy ◆ RURB design standards ◆ Governmental subsidy ◆ Governmental support	◆ The result of building retrofit ◆ Troubles and inconvenience	◆ Retrofit measures for a better indoor environment ◆ Retrofit measures for energy conservation ◆ Win-win techniques	◆ Retrofit benefits ◆ Happiness ◆ Productivity ◆ Satisfaction ◆ Changed energy bills
Issues	◆ Weak RURB policy ◆ Limited funds ◆ Rejections from residents	◆ No comprehensive and reliable RURB design standards ◆ Residents' diversity and rejection ◆ Low efficiency due to single-building scale ◆ High labour cost but no economic benefits	◆ Isolation with residents' diverse retrofit demands ◆ Lack of consideration of local advantages ◆ Lack of research funds	◆ Economic burden ◆ Individual preferences ◆ Will towards coordination ◆ The argument over retrofit benefits ◆ The argument over retrofit troubles ◆ No motivation

System Player	Policymakers	Designers & Engineers	Scholars	Residents
Demands	◆ Reduced energy consumption and carbon emission ◆ The well-being of urban citizens	◆ Reliable RURB policy ◆ Design standards ◆ Retrofit measures	◆ The practicality of developed techniques ◆ Subsidy for research into advanced retrofit measures	◆ Better indoor environment ◆ Well-being ◆ Accessibility ◆ Reduced energy bills ◆ Increase house value/price
Features	◆ Top-down administration ◆ Receive pressures from energy and climate crisis	◆ Empiricism ◆ Follow the demands of residents ◆ Follow the rules of policymakers	◆ Can solve technical problems ◆ Can select suitable retrofit measures	◆ Suffer from current poor conditions ◆ Local preferences & habits

In the view of four different system players, while the characteristics of ROIDF are clarified from SPA, the true RURB system cognition can be enhanced by a more comprehensive and rich description:

4.7.1. Governmental policymakers

Policymakers are the initiators and proponents to advocate the RURB activities in society. Policymakers hold both a significant budget and the burden of ambitious energy-saving and carbon emission reduction objectives from the central government. Policymakers are also the designers and enforcers of RURB regulations and standards. They need reliable evidence to help them formulate the policy content for the distribution of economic support.

Proven by policy review and interview survey results, although the current RURB policy content is weak and little implemented, the policy could yet be the most powerful force to push RURB development. The top-down administrative strength of the government is the most important feature of this system player role. As argued, the barrier between policymakers and other system players is caused by many issues: the lack of clear quantitative political objectives; financing protocols; the capability of departments, agencies, and industry; and misaligned incentives, similar to public building practice (Alam et al., 2019). Therefore, the retrofit output of 'design and implement improved and scientific policy' should still be the outcome because policymakers can enable top-down administration and a large amount of government support to reduce the economic burden of RURB of residents.

4.7.2. Designers and engineers

With their knowledge of retrofitting techniques, designers and engineers agree with the professionals who do the whole retrofit design and construction work. They play an important role as facilitators to achieve the objectives set for retrofitting. From the interviews, single building retrofitting can be easy after the building occupants agree to retrofit, as relevant technical and engineering approaches have been proven, developed, and practised.

However, there are many challenges within urban-scale retrofitting. Firstly, the scale of modern RURB design and engineering is still normally using the single building-by-building approach, so it is inefficient and lacks the universality to apply the developed designs and engineering works to other buildings. Secondly, the diversity of retrofit demands can cause many difficulties for designers and engineers when applying prevailing retrofit measures and arranging a retrofitting plan based on their previous experience. Also, the issue of limited finance needs to be considered.

4.7.3. Scholars

Built environment scholars have detailed knowledge of building retrofit techniques, but most of them are limited to the single building scale of academic research techniques. Therefore, the role of scholars is ‘developers’ to create new retrofit measures or improve the efficiency of energy conservation and comfort level of current retrofit measures. The outputs from scholars could be the advanced retrofit measures with modern technologies suitable for the local conditions, as they can extend the library of selections for RURB designers and engineers.

Yet currently scholars do pay not enough attention to the local, economic, and social situations of individual residents. As a result, academic achievements from scholars are slow and difficult to use in policymaking and building retrofit engineering. While scholars engage in academic research and create technologies for RURB, policymakers and residents may not have sufficient awareness, understanding, and economic resources to support the theory or applications provided by scholars.

4.7.4. Residents

Residents are the main payers and benefits receivers in the RURB system. Residents' opinions are the most important factor affecting RURB decision-making, and these social problems are much more complicated compared to those involved in retrofitting public buildings (Dunham-Jones and Williamson, 2008). The residents are the people who receive the final benefits from retrofitting and are the final decision-makers for RURB (Grosh and Glewwe, 2000), including reduced energy bills, improved comfort and living quality, and potentially increased happiness and productivity.

As mentioned, the extreme diversity that exists among the residents with multifarious education levels, incomes, living habits and behaviours, and thermal comfort requirements may pose many challenges to the designers and engineers who are retrofitting their houses. Due to the nature of shared ownership of apartment-type and tower-type buildings, cooperation from residents is the most essential to progress a RURB program. Since it is almost impossible to fully satisfy all the residents all the time and survey and identify the social-related issues within the retrofitting, communication, encouragement and motivation should be the most important concerns when working with this group of people. Yet these problems have not been fully studied and understood (Ma et al., 2012), and require a very comprehensive, scientifically designed, survey with a representative sample size to collect data for more reliable retrofitting design scenarios.

4.8. Results of System Interactions

Once the system entities and variables have their characteristics clarified and tagged on the system structure, their interactions can then be analysed to identify the benefits and problems; classified as 'behaviour' in the system thinking theory (Wright and Meadows, 2009). In this section, the system interactions are obtained by using the Causal Loop Diagrams (CLD) method based on the system cognition revealed by the SPA result.

4.8.1. Theories of system interactions

To acquire the system interactions, Sterman (2002) suggested applying a system thinking approach to model such a complex world. After reviewing the literature (Assaraf and Orion, 2005, Forrester, 1994, Werhane, 2008, Haraldsson, 2004, Tranfield et al., 2003, Williams et al., 2017, Maani and Cavana, 2007, Sterman, 2002, Jackson, 2003, Bureš, 2017) on system thinking approaches and the research into several theories by Williams et al. (2017), System Dynamics (SD) are found to be the typical system thinking theory used to understand and improve systems. Developed by Forrester (1994), SD has been proven by Wright and Meadows (2009) to be a developed research methodology to structure complex systems with involved elements and to understand system cognition. Furthermore, it finds solutions to systemic problems identified from the dynamic analysis of 'behaviours and outputs of system elements' over the studied period.

Among many SD approaches, Bureš (2017) supported the ability of the Causal Loop Diagrams (CLD) method to enable social researchers to identify the system dynamics and internal interactions. This system-thinking approach has proven to be a great assessment tool for policy intervention, decision-making, and the evaluation of renovation effects (Aikenhead et al., 2015, Paterson and Holden, 2019). It shows that CLD can clearly reveal the connections between system variables with feedback loops and nonlinearities, leading to its adoption by many researchers in other fields such as Liebovitch et al. (2020) in peace systems, S. Kim et al. (2021) in automotive retail forecasting, Setianto et al. (2015) in animal husbandry, and Viana (2017) in human science. Therefore, for this study, CLD can be used as an appropriate method to provide visual diagrams of the system structure and variables.

As the study from Haraldsson (2004) provides a developed research step for CLD drawing, the RURB entities should be defined with their individual characteristics, while the links connecting variables with both reinforcing and balancing feedback loops are followed. Based on the property of loops, it can be found that different interactions may amplify or dampen the effects of changes, moving the system away or towards the equilibrium point set within the purpose of the research. As Tranfield et al. (2003) and Haraldsson (2004) stated, the causal links between variables have one higher rank for finding the positive proportional relationship, or negative inverse relationship. Accordingly, the systemic problems can then be revealed as balancing loops within CLD pictures for further discussion and solutions.

The next three sections will reveal the interactions between system variables of RURB will be fully identified based on the system variables identified in section 4.3.3, using the CLD method. All the causal links and the feedback should be linked between variables by assumptions and should be quantified and justified by collecting information from the system players.

4.8.2. Detailed system variables and overall RURB system interactions based on SPA

As indicated in section 4.3.3, system variables of RURB within the defined system boundary in this study can be classified into seven categories: 1) retrofit measures, 2) retrofit benefits, 3) retrofit costs issues, 4) troubles from retrofit engineering work, 5) energy and carbon problems, 6) subsidies and support, and 7) local conditions. According to the rich description of the RURB system from SPA results, they can be expanded into more detailed system variables, matched with explanations and relations with their dominant system player, to become a total of 25 variables, shown in Table 4.9.

Table 4.9: Detailed system variables of RURB in this study

No.	System variable	Explanation	Dominant system player
1	National/local economic development	Overall economic level affects the attention to energy and carbon	Policymakers
2	Energy and carbon problems	Problems of energy crisis and climate changes caused by energy consumption and carbon emission	Residents
3	Demands for energy-saving	Solution for energy and carbon problems	Policymakers
4	RURB policies	Regulation and standards of RURB	Policymakers
5	Support and subsidy	Budget and help for RURB construction work	Policymakers
6	Retrofit techniques	Technologies for energy and built environment	Scholars
7	HVAC equipment and devices	The energy efficiency of HVAC equipment	Scholars
8	Building façade insulation	Thermal performance of external building façade	Scholars
9	Local climate conditions	Unique local conditions such as solar heat gain, air temperature, and humidity	-
10	Building operating energy	Energy use for operating residential buildings	Residents
11	Energy bills	Energy bill payments to residents	Residents
12	Residents' income	Residents' economic level	Residents
13	Current conditions of old residences	The current physical built environment of old urban residences (before retrofit)	-
14	Demands for indoor built environment improvements	Residents' demand for indoor thermal comfort, accessibility, and safety	Residents
15	Retrofit desire and decision-making (**DDMR**)	Residents' desire and decision-making of RURB works	Residents

16	Retrofit benefits: better living comfort and quality	Beneficial feedback to residents from RURB works	Residents
17	Retrofit measures of comfort, accessibility, and safety devices	Necessary measures to achieve retrofit demands (14)	Residents
18	Retrofit investment costs	Total investment costs of RURB for material, equipment, temporary move--out, and techniques	Residents
19	Retrofit construction works	Construction and installation engineering works	Designers & Engineers
20	Design and labour costs	Costs of RURB design and labour	Designers & Engineers
21	Troubles and inconvenience	Noise, temporary move-out, temporarily disabled functions, and accessibility issues caused by construction works	Designers & engineers
22	Time cost from retrofit works	Time to end the trouble and inconvenience (21)	Designers & Engineers
23	Local advantages	Unique local advantages (such as energy and weather resources)	-
24	Local energy prices	Unique local energy prices	-
25	Preference and local habits	Unique local preferences and habits of residents	Residents

Following the defined system boundary and results from SPA, the RURB system interactions can be obtained as the 'overall CLD figure', with the causal links of system variables matched the four system players, matched in four colours. The positive flows are presented as lines with plus signs (+), and the negative flows are presented as lines with minus signs (-), as shown in Figure 4.10:

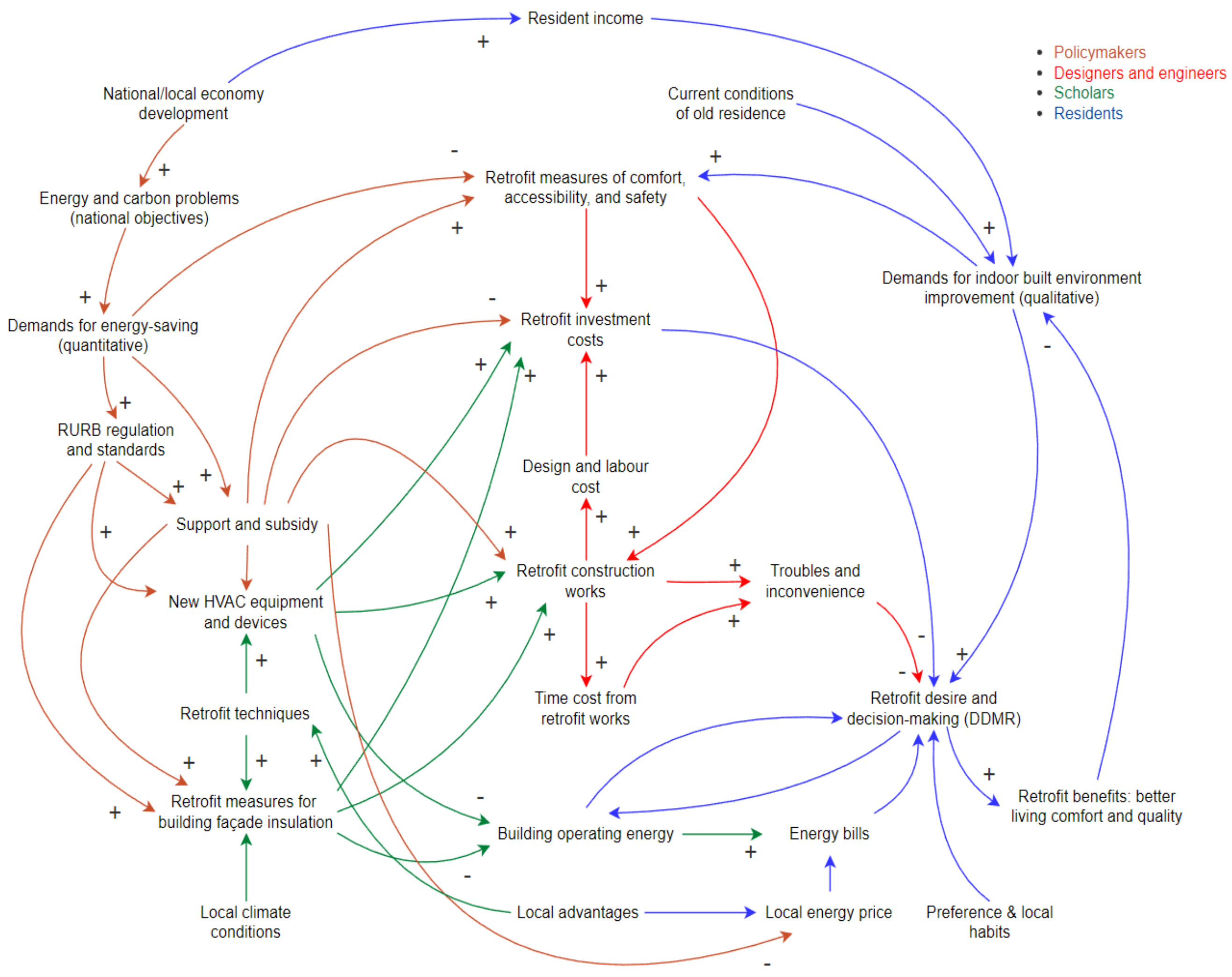


Figure 4.10: The overall CLD to describe the RURB system interactions

The above overall CLD can be found as a visible ROIDF of the RURB system of section 4.7. Figure 4.10 presents the most completed and complicated retrofitting mode that all possible system variables involved. Variables related to and embodied with the policymakers have their causal links marked as brown lines, scholars as green lines, designers and engineers as red lines, and residents as blue lines. This overall CLD is a grand picture of causal links between 25 detailed system variables. However, the overall CLD of Figure 4.10 can be argued to be overcomplicated. All system variables are ideally and simultaneously introduced into the system interactions. Hence it is difficult to clearly identify the balancing and reinforcing loops among chaotic lines for further analysis.

To clarify and simplify the overall CLD figure of RURB for a more straightforward picture of RURB system interactions, the ROIDF data of four system players are introduced to match their own embodied system variables and structure the privilege boundary (exclude the outputs) of these non-loop effects, as shown in Figure 4.11.

According to the SPA results of ROIDF characteristics, in Figure 4.11, four system players are individually assigned with their embodied system variables (within the box) as the dominant system player mentioned in Table 4.10. Their variables of outputs revealed in Table 4.9 are put outside of boxes with causal links from the boxes to clarify their belonging system players. It is also worth noticing that the qualitative retrofit benefits have causal links to subjective benefits of residents (such as happiness, productivity, and satisfaction) which cannot be measured in this study, hence they can be integrated as one main output - retrofit benefits of better living comfort and quality - during CLD drawing process.

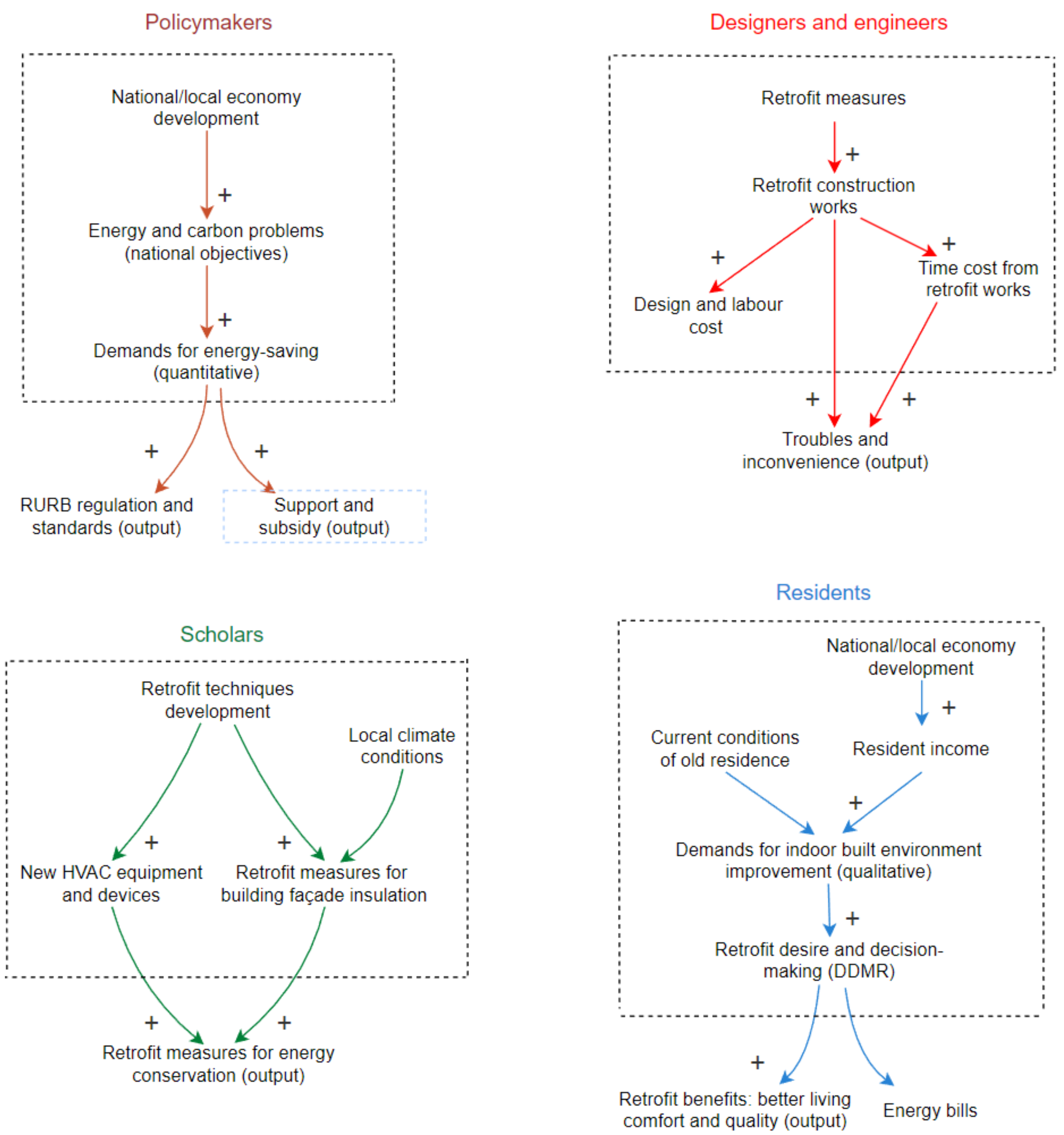


Figure 4.11: System players and their embodied system variables from ROIDF result

Moreover, in real circumstances, the review documents of RURB projects indicated that not all system variables mentioned in the overall CLD are always involved in engineering practices. For example, many RURB projects were reported to be completed by only residents, while they have received little or nothing support and subsidies from the local government. In this case, there were no links between policymakers and scholars. To represent more realistic RURB situations in CLD, two retrofit models are hence identified based on the driven system players of RURB (similar to the RURB system modes mentioned in section 4.2.2): 1) the resident-driven retrofit, and 2) the government-driven retrofit. Subsequently, the third and 'ideal' retrofit model in which all system players cooperate can be hence created and argued to attempt to find the possible solutions for RURB's current systemic problems and further improve policymaking and efficiency.

4.8.3. The Resident Spontaneous Retrofit (RSR) model

Without the interactions from other system players, residents are the natural initiators of RURB, and so provide a primary input to drawing a CLD. Accordingly, the RSR model is presented by the CLD displayed in Figure 4.12. As stated by Haraldsson (2004) and Sterman (2002), each associated flow of causal links and feedback has its polarities, defined as positive (+) and negative (-) effects. To further understand this complex system, Sterman (2002) has identified that feedback loops can have two different attributes: the reinforcing loop and the balancing loop. A reinforcing loop represents the enhancing or declarative actions or influences on the next variable while a balancing loop shows that the connections will be self-balanced to refuse changes to current loops when new mechanisms appear. The reinforcing loops are presented as grey-black lines (+) and the balancing loops are presented as blue-green lines (-) on the CLD.

However, although the RSR model is the most common and realistic situation, it also exhibits wild, uncontrollable, and unpredictable complications. Owners of old urban residences will spontaneously start to retrofit their houses for many individual reasons, including aspiring to a better quality of life, more functions, better thermal comfort, changing the built environment, changes to house planning, or creating a more sustainable and energy-efficient built environment. In this model, the impacts of residents' opinions are significantly amplified as they become the decision-makers and responsible for the majority of the design and cost; however, the strength of policy support and guidelines is weakened. Therefore, the resident is much more biased - as the receiver, they may slowly and spontaneously decide to retrofit their home despite the influences from other system players.

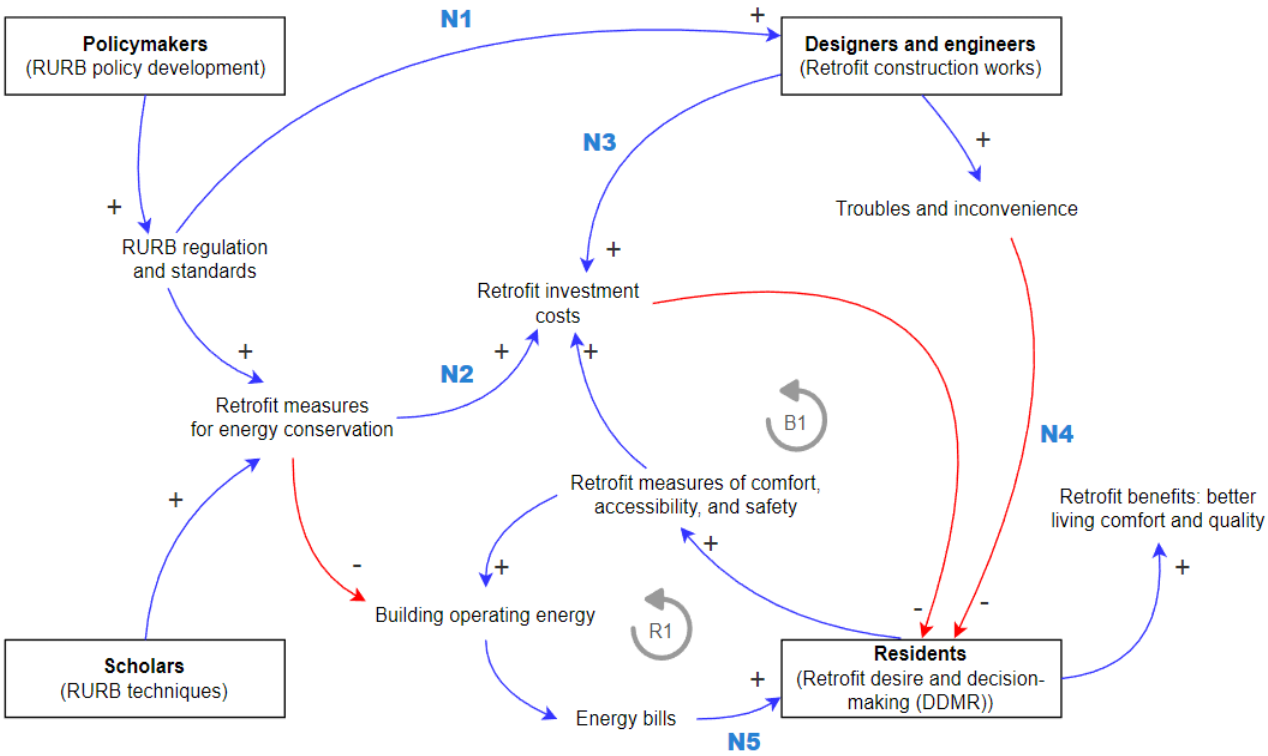


Figure 4.12 CLD for the Residents' Spontaneous Retrofit (RSR) model

From the CLD in Figure 4.12, the feedback loops can be more straightforward as residents benefit from positive effects (+, blue) from the retrofit and suffer negative effects (-, red) from retrofit costs. In the RSR model, as reviewed, system players are isolated and have no cooperative relationship – policymakers publish standards, scholars develop retrofit techniques, and residents select and make retrofit decisions based on their own demands. Therefore, there is one significant balancing loop B1 hinders the residents' decision-making of RURB due to the high investment costs, while another loop R1 may also increase or reduce the energy bills, as in Table 4.10:

Table 4.10: Loop flows of the RSR model

No.	Dominant system player	Causal loop flow	Property
B1	Residents	Residents → Retrofit measures of comfort, accessibility, and safety → Retrofit investment costs → Residents	Balancing (-)
R1	Residents	Residents → Retrofit measures of comfort, accessibility, and safety → Building operating energy → Energy bills → Residents	Reinforcing (+)

However, non-loop causal links are found among flows shown in Table 4.11. The flows N1 and N2 related to policymakers are both positive to increase total retrofit investment costs by increasing the demands of retrofit techniques. Meanwhile, the N3 and N4 flows present the conventional linear RURB engineering approaches, which will bring construction costs, troubles, and inconvenience to negatively hinder the decision-making of residents. Only the scholars' N5 flow may contribute to the reduced energy bills from the retrofit measures for energy conservation.

Table 4.11: The non-loop effects of the RSR model

No.	Dominant system player	Causal loop flow	Effect
N1	Policymakers	Retrofit regulation and standard → Designers and engineers	Positive
N2		Retrofit regulation and standard → Retrofit measures for energy conservation →Retrofit investment costs	Positive
N3	Designers and engineers	Designers and engineers → Retrofit investment costs	Positive
N4		Designers and engineers → Troubles and inconvenience → Residents	Negative
N5	Scholars	Scholars → Retrofit measures for energy conservation → Building operating energy → Energy bills → Residents	Positive

It is proven that this 'wild developing' RSR scenario is naturally slow and inefficient due to the lack of feedback from linear effects between system players. This phenomenon of multiple and no-feedback flows shows that it is impossible to fully describe and understand the complex world of RURB systems from the viewpoint of an isolated system player. These non-loop effects should be highlighted and defined as the serious systemic problems hidden in reality which interfere with RURB developments. Therefore, for future RURB development and policymaking, solutions have to be found to convert these effects into positive ones for residents.

4.8.4. The Government-Driven Retrofit (GDR) model

The RSR model shows the natural situation of RURB system interactions and systemic problems without extreme impacts caused by other system players. However, there are different anthropic factors which act as driving forces to influence the development of building retrofit. As discussed in SPA, the top-down administrative impact of governmental policy is one of the most common and dominant forces in China to effectively increase the speed of RURB development by providing retrofit design standards and subsidies. As argued, two variables are introduced in the GDR model since the RURB policy and standards have a great ability to relieve or solve the systemic problems of the dominant balancing loop of retrofit cost issues, which prevent residents from making the decision to retrofit.

- Energy and carbon problems are external pressures mentioned in RURB demands resulting from SPA policymakers.
- Great support and subsidy are outputs provided by policymakers to increase the speed of RURB progress.

Accordingly, the GDR model maximises the strength of the government and has its CLD shown in Figure 4.13 and Table 4.12. The GDR model represents residential buildings which are going to be retrofitted driven by specific reasons decided by the government, while relevant retrofit engineering works are usually supported by extremely powerful governmental pressures. The two main outputs of SPA policymakers: reliable RURB design standards and comprehensive governmental subsidies, are enhanced. In this case, the top-down administration from the government and relevant policy could provide great efficiency to solve some of the RURB problems including finance, engineering designs, and temporary resettlement of the residents, which can relieve the effects of loops N1 and N2 in the RSR model.

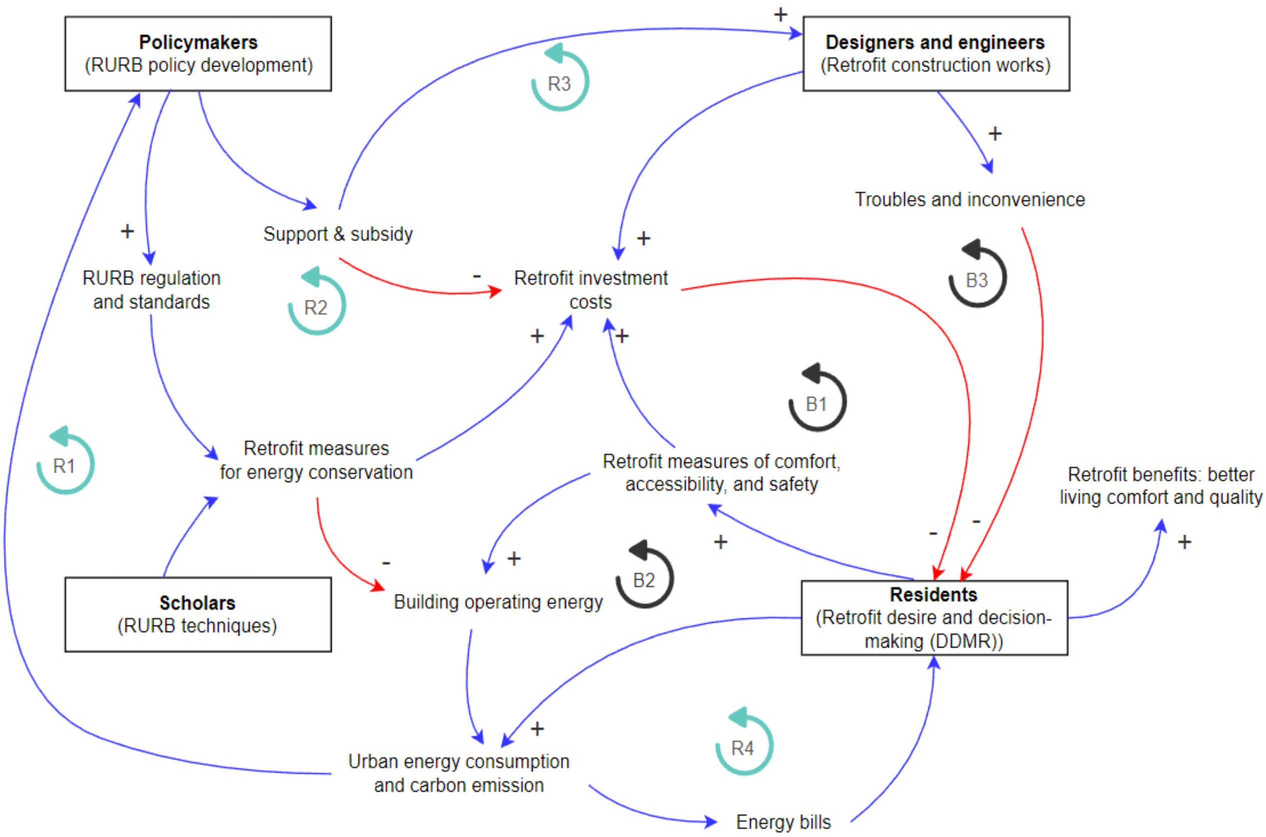


Figure 4.13: CLD of the Government-Driven Retrofit (GDR) model

From the SPA documents and survey results, this model has been verified as the currently most popular situation for the majority of building retrofit projects and studies (Alam et al., 2019), which is faster and more easily achieved in reality compared with the RSR model. The GDR model has the completed loop flow for policymakers, which involves energy and carbon problems as external factors (or pressures from the global energy and climate crises). This variable can positively guide the development of RURB policy, while policymakers have to design and implement new and more strict retrofit design standards, as well as governmental support and subsidy for RURB designers, engineers, and residents. Compared with the RSR model, the GDR model has an increased number of reinforcing causal loop flows which can effectively increase the speed and efficiency of RURB development.

Table 4.12: Loop flows of the GDR model

No.	Dominant system player	Causal loop flow	Property
B1	Residents	Residents → Retrofit measures of comfort, accessibility, and safety → Retrofit investment costs → Residents	Balancing (-)
B2	Residents	Residents → Retrofit measures of comfort, accessibility, and safety → Urban energy consumption and carbon emission → Energy bills → Residents	Balancing (-)
B3	Policymakers	Policymakers → Support and subsidy → Designers and engineers → Troubles and inconvenience → Residents → Urban energy consumption and carbon emission → Policymakers	Balancing (-)
R1	Policymakers	Policymakers → RURB regulations and standards → Retrofit measures for energy conservation → Building operating energy → Urban energy consumption and carbon emission → Policymakers	Reinforcing (+)
R2	Policymakers	Policymakers → Support and subsidy → Retrofit investment costs → Residents → Urban energy consumption and carbon emission → Policymakers	Reinforcing (+)
R3	Policymakers	Policymakers → Support and subsidy → Designers and engineers → Retrofit investment costs → Residents → Urban energy consumption and carbon emission → Policymakers	Reinforcing (+)
R4	Residents	Residents → Urban energy consumption and carbon emission → Energy bills → Residents	Reinforcing (+)

In the GDR model, the power of improved RURB regulation and standards, as well as the governmental support and subsidy will cause significantly reduced urban energy consumption and carbon emission due to the retrofit demands of policymakers from SPA. The interaction loops of R1, R2, R3, and R4 are hence raised to reduce both retrofit investment costs and building operating costs for residents, as the solutions for B1 and B2 of residents' issues. Yet the support of construction works of building façade retrofit may cause more troubles and inconvenience to residents, as the loop B3, which is negative for the system. At last, the new non-loop effects of support and subsidy N6 and N7 represent the one-off governmental help in the economy and retrofit construction works, but they have no feedback from other system players, as in Table 4.13:

Table 4.13: New non-loop effects of the GDR model

No.	Dominant system player	Causal loop flow	Effect
N6	Policymakers	Policymakers → Support and subsidy → Retrofit investment costs	Negative
N7	Policymakers	Policymakers → Support and subsidy → Designers and engineers	Positive

4.8.5. The Cooperative Retrofit (CR) model

SPA results have provided a large amount of informative and realistic data which can be very useful for professionals to adjust and design future RURB policies. Yet, as Sterman (2002) suggested, it is important to highlight and absorb the advantages from the foresight provided by system thinking results, create more feedback loops, and avoid the problems found. Since the result of the SPA of RURB professionals has revealed many critical problems, it has subsequently been necessary to find corresponding solutions to further improve RURB development based on the current GDR model.

From the SPA result, RURB is currently still developing slowly under the GDR model above, while RURB policymakers and scholars work individually without cooperation and communication. Furthermore, the SPA result shows that, although the majority of opinions and thoughts provided by professionals have been verified by residents who share similar feelings, there are still some ambiguities between different RURB system players. This means that there are still many conflicts that can be revealed and solved to further increase the effectiveness of RURB if all four system players can cooperate - thus a cooperative model is created which breaks the isolation between the system players.

In this new CR model, the relevant ROIDF of all four system players are included in Figure 4.14, similar to a combination of the overall CLD of the RURB system in Figure 4.12 and 4.13:

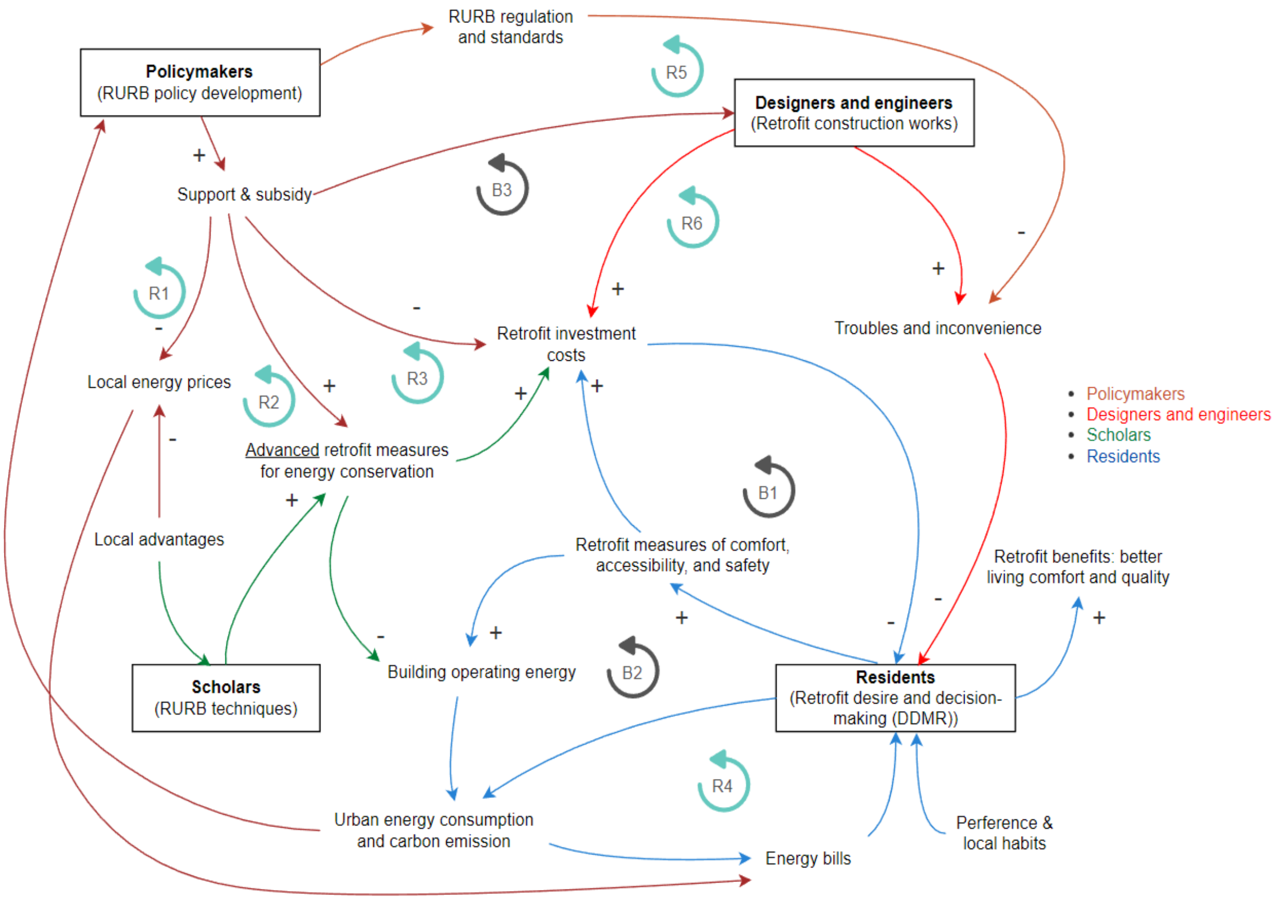


Figure 4.14: CLD of the Cooperative Retrofit (CR) model

The above CR model has the RURB causal loops enhanced with interactions between the four system players by improving the existing variables and introducing new solution themes revealed by the SPA result:

1) Enhanced subsidy: as various forms of governmental support are connected with designers and residents, the enhanced subsidy not only directs all the money to the residents, but it may have further positive impacts on the price of energy use, material, construction work, and HVAC equipment. The enhanced subsidy hence has two new motivating effects: to reduce local energy prices for residential buildings and to provide discounts for advanced retrofit measures for energy conservation.

2) Local issues: as one of the features of residents' SPA ignored by historical RURB policymaking, projects, and studies, local advantages can be revealed from a qualitative survey as 'feedback loops from residents' to effectively improve the

selection of retrofit measures and motivation.

3) Advanced retrofit measures: as improved win-win retrofit measures produced by RURB scholars' output, based on both their knowledge and local advantages they can be provided as qualitative data from residents' SPA describing local preferences and habits. These measures are more acceptable and appropriate to fit the demands of other system players.

4) Reduced energy bills: resulting from both subsidy and advanced retrofit measures, the cooperation between policymakers and scholars can enhance this variable to reinforce the balancing loop (B2 in RSR), since it can help motivate the residents by partly reducing the economic pressure from building operating costs, as well as to achieve the political objectives for policymakers.

5) Reduced difficulties during construction work: as the outcome of the new linkage between policymakers, designers, and engineers, reliable and easy-to-use RURB standards which satisfy the demands of designers & engineers can significantly increase RURB efficiency and reduce the problems (e.g., time-cost, engineering troubles), and so directly improve residents' decision making for a retrofit as they see it as an important issue.

The sorted loop flows are shown below in Table 4.14:

Table 4.14: Loop flows in the CR model

No.	Dominant system player	Causal loop flow	Property
B1	Residents	Residents → Retrofit measures of comfort, accessibility, and safety → Retrofit investment costs → Residents	Balancing
B2	Residents	Residents → Retrofit measures of comfort, accessibility, and safety → Urban energy consumption and carbon emission → Energy bills → Residents	Balancing
B3	Policymakers	Policymakers → Support and subsidy → Designers and engineers → Troubles and inconvenience → Residents → Urban energy consumption and carbon emission → Policymakers	Balancing
R1	Policymakers	Policymakers → Support and subsidy → Local energy prices → Energy bills → Residents → Urban energy consumption and carbon emission → Policymakers	Reinforcing
R2	Policymakers	Policymakers → Support and subsidy → Advanced retrofit measures for energy conservation → Building operating energy → Urban energy consumption and carbon emission → Policymakers	Reinforcing
R3	Policymakers	Policymakers → Support and subsidy → Retrofit investment costs → Residents → Urban energy consumption and carbon	Reinforcing

		emission → Policymakers	
R4	Residents	Residents → Urban energy consumption and carbon emission → Energy bills → Residents	Reinforcing
R5	Policymakers	Policymakers → RURB regulations and standards → Troubles and inconvenience → Residents → Urban energy consumption and carbon emission → Policymakers	Balancing → Reinforcing
R6	Policymakers	Policymakers → Support and subsidy → Designers and engineers → Retrofit investment costs → Residents → Urban energy consumption and carbon emission → Policymakers	Reinforcing

The CR model also has new non-loop flows to indirectly enhance the residents' DDMR by introducing new detailed system variables of local conditions, as shown in Table 4.15:

Table 4.15: New non-loop effects of the CR model

No.	Dominant system player	Causal loop flow	Effect
N9	Scholars	Local advantages → Scholars → Advanced retrofit measures for energy conservation	Positive
N10	Residents	Local advantages → Local energy prices → Energy bills → Residents	Negative
N11	Residents	Preference & local habits → Residents → Retrofit measures of comfort, accessibility, and safety devices	Positive

In the CR model, the governmental subsidies can be various and scientific to support the reduced energy bill, reduce problems in construction work, and the reduced negative effect of retrofit costs on the DDMR, as shown in CLD loops of R1, R2, R3, R5. As the outcomes of breaking the barriers caused by isolation, balancing loop B3 in the GDR model can be transferred into reinforcing loops R5 by more reliable RURB standards. Moreover, new reinforcing loops R2 are raised to increase the efficiency of retrofit techniques with energy-saving purposes by introducing advanced retrofit measures. As a causal relationship, the advanced retrofit measures are linearly produced by RURB scholars who rely on data about local advantages provided in the qualitative data on residents' desire for retrofit. Ideally, this improvement of retrofit measures can also relieve the constant negative effects connected to retrofit cost issues through the positive effect of the reduced energy bill and help reduce the economic pressure on the residents, as from R1 and R4.

4.9. Summary

This chapter developed a RURB system perspective theory to clarify the RURB system definition, to understand the complex system cognition and interactions and to provide a theoretical basis for the policymaking and design for retrofitting old urban residential buildings. The system perspective successfully analysed the hidden systemic problems for future policymaking. The summary can be drawn as follows:

- Retrofitting of urban residential buildings (RURB) was proposed and justified by the inductive reasoning method based on current documents to become a complex and cooperative system involving both professionals and residents. Following the logic of positivism, the RURB system was objectively stated with a clear system definition and system boundary, rather than as the conventional thinking underpinning a political task or linear engineering work.
- The system cognition for retrofitting urban residential buildings was revealed and clarified by adapting the System Player Analysis (SPA) method based on the CLA method and social survey data. The system cognition was comprehensively described and explained based on the four core system players along with five-layered characteristics based on their Roles, Outputs, Inputs, Demands and Features (ROIDF).
- The RURB system interactions between all four system players were analysed using the CLD method based on three different models related to the main system driving force: the resident spontaneous retrofit model, the government-driven retrofit model, and the cooperative retrofit (ideal) model. Three main systemic problems were hence revealed: 1) cost and limited retrofitting funds, 2) conflict of retrofitting demands between policymakers and residents, and 3) conflict between thermal comfort and energy bills.

Importantly, this chapter presented a novel and extendable theoretical framework to assume, justify and finally clearly understand a complex system, based on the convergence of inductive reasoning and the system perspective. Furthermore, the adapted system player analysis was justified as being suitable to clarify and understand a complicated system involving different groups of people. The ability to reveal systemic problems and discover possible solutions using causal loop diagrams were also evidenced. Therefore, this theoretical framework combining SPA and CLD can be extended to other research fields which have similar problems of a complex nature. In the next chapters, the developed RURB system theory will be verified with a case study following the logic of positivism.

5. The Case Study in Chongqing City, China

5.1. Introduction

Following the positivist philosophy for building energy studies, the established process of proof should be an experimental platform to evidence the rationality and reliability of a developed statement or theory. Since the above chapter has justified and clarified the RURB system, it is necessary to use a case study to verify the developed RURB system theory. In this case, a complete and coherent RURB engineering process is established, simulated and analysed.

This chapter addresses research question three: how to describe the 'before' view of old residences? - it aims to provide urban residential building modelling to present the 'before-retrofit stage' during the RURB process (shown in Figure 3.2 of the methodology chapter). Initially, an urban city zone with a long history of urban development and different types of old residential buildings was selected as the case study area. Secondly, the brief building models in the studied area can be captured from the satellite GIS database. As argued in Chapter Two, the GIS models have problems identifying the function of buildings (in this study considered to be public and residential) and the built age of the buildings. Therefore, the field survey method was applied to accurately identify the existing problems and the building envelope conditions. Hence the old residential building models with a clear 'old degree' index can be obtained. Then, to scientifically simplify the overcomplicated diverse building models, surveyed building models were classified into four different representative building types by using the K-means clustering method.

Afterwards, as the preparation steps for retrofit simulation, seven different retrofit scenarios were designed and adapted to the system interactions revealed in Chapter Four. The baseline scenario is designed to describe the current building conditions based on China's old building regulations and the field survey results. Two RSR models: 'Resident Spontaneous Retrofit Scenarios' were designed following the questionnaire survey result, they show retrofit packages decided by residents only, who may not have enough knowledge that relates to the context of the built environment. Two GDR models: 'Government Driven Retrofit Scenarios' were designed in which the old residences would be retrofitted according to the government plans (using a building index guided by the newest building design code and regulations). They represent the gap between old buildings and new buildings. Finally, two CR: 'Cooperative Retrofit Scenarios' where four RURB system players cooperate to retrofit the old residences were designed. Ideally, they can apply advanced techniques, provide governmental support and eliminate the objections from residents to reach the highest energy conservation objectives and the best improvements in living comfort.

5.2. Selection of case study area

An urban city zone with different types of old residential buildings should be selected as the case study area. This area needs to meet the following requirements:

1) A high population density, busy, old urban area with a long development history.
2) There are many 'significantly old' residential buildings with more than 20 years of built age, without proper maintenance and retrofit.
3) The climate conditions in the case study zone are considerably severe both in summer and winter, making mechanical heating and cooling measures necessary.
4) It is easy to assess and survey the target zone. The GIS building models in the studied area can be captured from the satellite GIS database.
5) This area has available weather condition records for energy simulation.

Based on the requirements above, this research selected a busy urban zone with lots of old residential buildings as the case study area, located around the campus of Chongqing University, Shapingba District, Chongqing, in China's HSCW climate zone. Since Chongqing University was established in this area in 1929, this urban area had an extremely long history of development. Currently, due to its location and the advantage of education facilities, this area is very crowded with high housing prices. The building stock has many old, historical and dilapidated residential buildings with conspicuously messy external building façades, which makes it very suitable for this study.

Figure 5.1: Satellite image of the selected urban zone with a high density of old residences

The building models captured from open-access satellite image sources are imported into the GIS and Photoshop software to create a visual map of local old residences. By filtering the function of buildings and selecting only the residential buildings, the final buildings considered for the field survey in this study are marked with white building colour and blue frames, as shown in Figure 5.2:

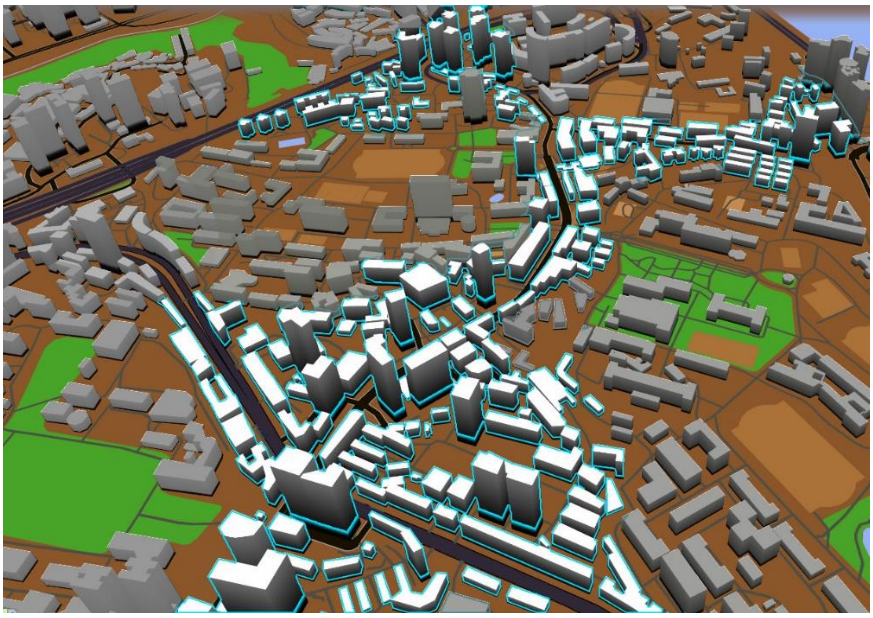


Figure 5.2: Developed map of old urban residence models for field survey

5.3. Residential building typology

As argued in Chapter Two, the oversimplification risk is a problem found in current studies of urban-scale buildings. However, the lessons from Nageler *et al.* (2017) and Mastrucci *et al.* (2014) prove that the raw, amply-detailed, building models captured from the GIS technique can be considered overcomplicated for the building energy simulation and calculations. Since the national BEES has not issued an official definition of 'old residences' with reliable building conditions, the old residences used for the case study in this area need to be scientifically simplified by using the building typology method.

5.3.1. Field survey

For urban-scale research, it is necessary to scientifically simplify the overcomplicated diverse building models and classify them into different representative building types as "reference buildings". Current approaches to identifying "old residences", however, can be criticised due to their unclear definition and lack of quantitative measurements. In the case area in the hot summer and cold winter climate zone, residential buildings did not have strict design standards until 2001. The majority of the current building simulation studies used GB-50189-2005 to set the building façade parameters of very old buildings. Therefore, although GB-50189-2005 is a public building standard, it has become the only official source for building parameters from 1980 to 2005 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2005). The accuracy and rationality of this reference in representatively describing all types of urban old residences are questionable.

Therefore, a field survey is necessary to collect more realistic data on physical building conditions and façade parameters. The number of floors in a building and the external window forms are very conspicuous indications of a building's age based on past limited construction techniques; moreover, the window is the most important building façade feature which has the greatest impact on the indoor cooling and heating load. Furthermore, compared with the new buildings, the old buildings have many quantifiable old characteristics, such as wall corrosion and no thermal insulation, as shown in Figure 5.3. While the definition of 'old' is difficult to obtain and describe, it is necessary to introduce and quantify the concept of 'old content' and their 'degree of old' in the residences.

Figure 5.3 Examples of 'old content' characteristics in the case study zone

Currently, there is no design manual or building standard that can be used to describe and quantify factors such as 'ageing', 'obsolescence' or 'deterioration' of the building façade, built environment and lack of functionality caused by development. Therefore, due to the inability to access the indoor environment of each household, this field survey collected 100 old residential buildings in the case study zone with their external walls, external windows, number of floors and the installation of electric lifts containing old features. The quantification concept of 'old degree' is defined using a scoring approach similar to the developed green building assessment tools such as BREEAM, LEED and CGBL. During the field survey process, a total of 19 found components can be described as "old content". These old contents can be linked to the five influence factors: energy, comfort, functionality, safety and environment, as displayed in Figure 5.4.

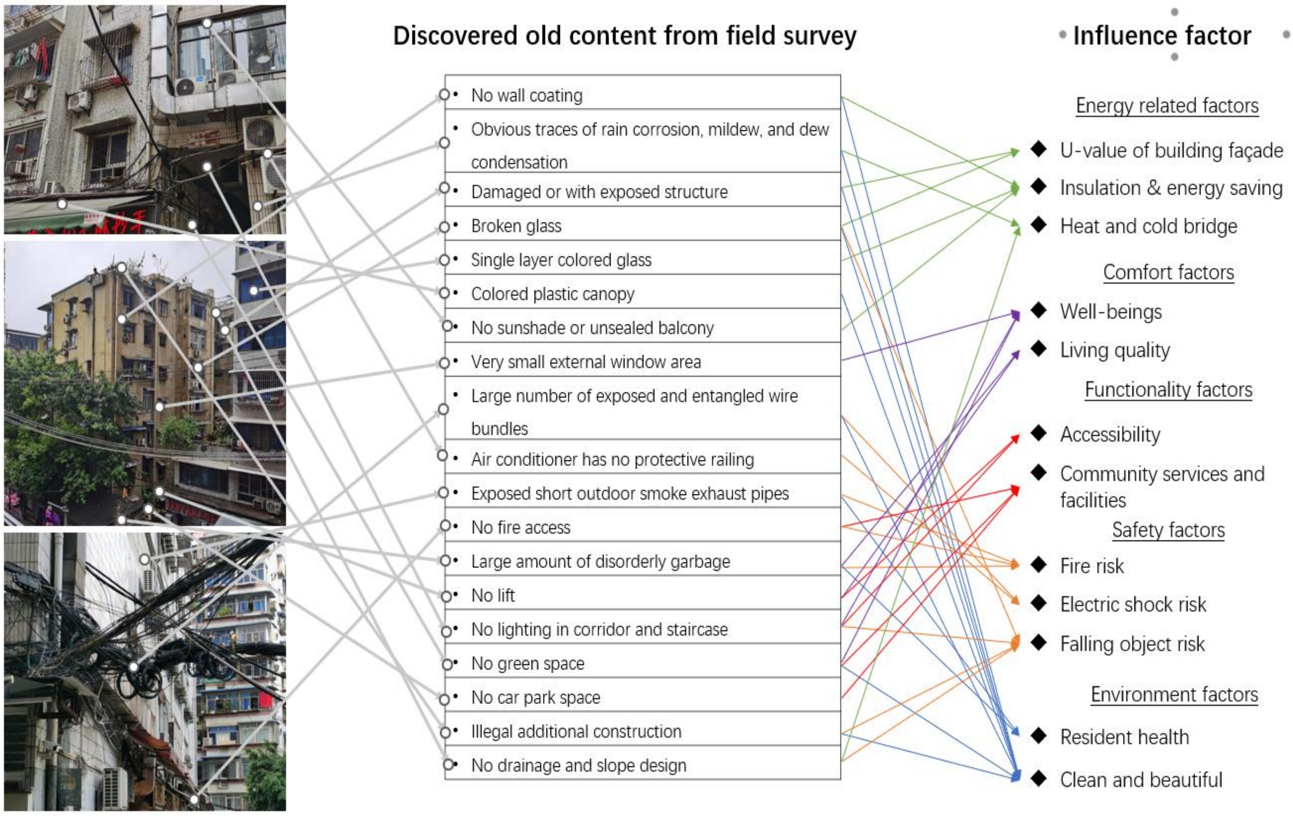


Figure 5.4: 'Old content' features discovered from the field survey and their influence factors

Based on the discovered from the field survey, the residences can be listed and assigned scores based on the review of current green building scoring methods. Briefly, each influence factor is given one (a total of 36) points to the related old content to compose the old degree score method, shown in Table 5.1.

Table 5.1: Scoring method related to the content of old in old residences

Content	Old content	Old degree score Energy	Comfort	Function	Safety	Environment
External Wall	1) No wall coating	1				1
	2) Obvious traces of rain corrosion, mildew, and dew condensation	1				1
	3) Damaged or with exposed structure	1				1
External Window	4) Broken glass	1			1	1
	5) Single-layer coloured glass	1				
	6) Coloured plastic canopy					1
	7) No sunshade or unsealed balcony	1				

	8)	Very small external window area		1			
Electricity	9)	A large number of exposed and entangled wire bundles				1	1
	10)	Air conditioners have no protective railing				1	
	11)	Exposed short outdoor smoke exhaust pipes				1	1
Fire safety	12)	No fire access			1	1	
	13)	A large amount of disorderly garbage		1		1	1
Accessibility	14)	No lift		1	1		
	15)	No lighting in the corridor and staircase		1	1	1	
Public space	16)	No green space		1	1		1
	17)	No car parking space			1		
Roof	18)	Illegal additional construction				1	1
	19)	No drainage and slope design	1			1	
Total old degree			7	5	5	9	10

Accordingly, there are three building variables surveyed to describe the building conditions of old residences: 1) the number of building floors, 2) external window form and 3) the building’s “old degree”. The variable “number of building floors” should be an integer; the external window form has three types and the building's “old level” has a maximum score of 36. The *K-means method* from the Statistical Product Service Solutions (SPSS) platform, following the research results and suggestions from Ghiassi and Mahdavi (2017) and practices from Li *et al.* (2018b), is highly effective in accurately clustering the reference buildings. Once the building types are clustered, reference buildings can be acquired and selected to identify the baseline scenario, as the current circumstances of urban old residences.

Moreover, extra adjustments were applied to the 100 surveyed buildings based on four extra rules: 1) the old residences with less than three floors were removed from the list of clustering due to their low land and retrofit values; 2) the temporary and dangerous residential buildings such as prefabricated houses are not considered due to their low land value and building life; 3) the historical and cultural old residences are not considered because of the relevant protection regulations and 4) the old residences that had been recently retrofitted were also omitted. Finally, 81 buildings were used for the K-means clustering method.

5.3.2. Results of clustered types of old residences

Firstly, based on field survey results and the K-means clustering method, there are four clusters of reference building types classified to represent the current circumstance of old building conditions (see Table 5.2) and used as the building models for the Baseline Scenario.

Table 5.2: Clustered reference building types

	Floor number (Integer)	Exterior window form	Old degrees (Integer)	Reference building type and shape
Cluster 1 (C1)	6	Coloured single glazing	30 (29.87)	Dilapidated, point type
Cluster 2 (C2)	8	Coloured single glazing	28 (27.73)	Dilapidated, slab type
Cluster 3 (C3)	10	Transparent single glazing	20 (19.52)	Old, slab type
Cluster 4 (C4)	30	Double glazing	10 (9.91)	Old, point type

1) Clusters 1 and 2: **Dilapidated Apartment**

Figure 5.5: Cluster 1 of Dilapidated Apartments and the reference building

From the historical building design code and Chinese governmental statistics, the 'apartment' is the most popular residential building type in cities. Slab-type apartments with eight floors were frequently built to replace bungalows and point-type residences with six floors (or seven floors with the first floor being commercial use, soviet-type buildings) to increase the urban population density from 1980 to 2000. In history, the majority of these residences have extremely bad façades due to poverty and the absence of BEES. From the field survey process, these residential buildings are found to be very decrepit, damaged and with a dirty building envelope, and they also rarely have any thermal insulation, shockproof features or any fire protection measures. In addition, these very old apartments have no accessibility facilities such as lifts, no public facilities such as green space, car park space and fire access. Accordingly, these buildings are classified as “dilapidated apartments” and represent the worst situation of the built environment.

Based on the clustering method results, this old urban residence type has an average old degree of 30/36 (as in Figure 5.5) to 28/36 (as in Figure 5.6), which contains almost all possible old content in residential buildings. It proves that the current literature describing the building conditions of old urban residences may not be reasonable. The clear situation of these old residences can be even worse compared to the 1980s old buildings mentioned in the related BEES.

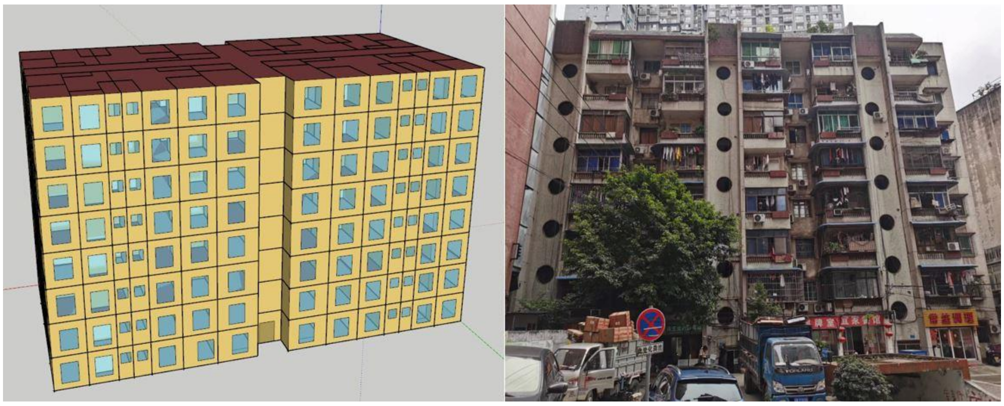


Figure 5.6: Cluster 2 of Dilapidated Apartments and the reference building

Moreover, it is worth noticing that the actual sizes of external windows in old urban residences were found to be smaller than what looks like a fully-glazed balcony from the field survey. It was found that the households prefer to seal their balcony close to the roadside with full glazing walls to reduce noise and dust issues. For the old urban residences located away from the street, the number of sealed glazing balconies was reduced. Therefore, the size of the external window in old urban residences should be considered small based on their original condition, as shown in Figure 5.7.

Figure 5.7: The real size of external windows in an old urban residence

2) Cluster 3: **Old Apartment**

3) Between 1995 and 2005, the modern concept of the 'residential building community', (similar to the housing estate in European countries) was developed and became popular as China's economy developed. Also, with the development of civil engineering techniques and the growth of China's economy, there were significant improvements in the national residential building standards. Therefore, many slab-type apartments with around 10 floors have been widely built and become the most representative residential building type in cities, as shown in Figure 5.8.

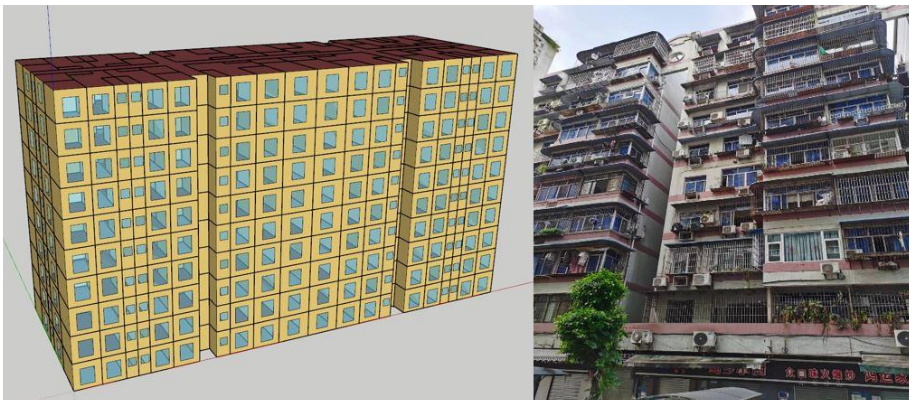


Figure 5.8: Cluster 3 of Old Apartments and the reference building

In the case study urban zone, this old apartment building type has the highest number among the 81 surveyed residences. Their physical building conditions are better than the 6- and 8-floor dilapidated apartments, with an average of 20 old degrees. The structure of the external walls was changed to solid clay brick from lime sand brick. The blue-coloured single-glazing windows were eliminated and replaced with transparent single-glazing windows. In summary, the building condition index of these old apartments is very close to the BEES of JGJ134-2001.

4) Cluster 4: **Old Tower**

Old tower refers to point-type high-rise buildings with more than 12 floors and multiple lifts in the initial design. Based on the historical development of reinforced concrete structure technology, this kind of tower building (with the limitation of 100 metres in height from BEES in 2000) became popular to deal with the rapid urbanization rate in modern China after 2000, as in Figure 5.9 (China Academy of Building Research, 2010). The household density in these old tower buildings is much higher than in apartment buildings

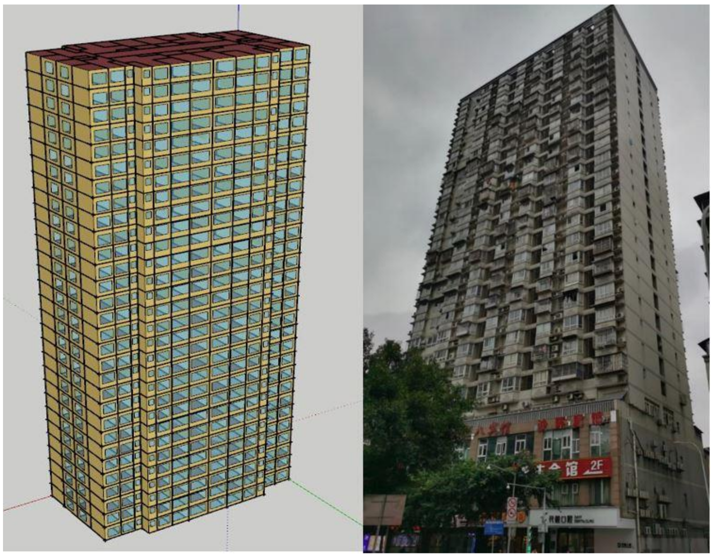


Figure 5.9: Cluster 4 Old Tower and the reference building

Although old towers have the best built environments compared with Clusters 1,2 and 3, the high number of floors makes the construction works of retrofitting the building façade very difficult and dangerous. Replacement of external windows and external air conditioners requires specific work-at-height engineering to avoid falling objects. Therefore, in the long-term view for future energy saving, old tower residential buildings are the most difficult residence type to be retrofitted, but the retrofit benefits for these buildings may also be the highest due to the high population density.

Secondly, to identify the shape and physical building conditions in the building modelling process, four representative old buildings were selected accordingly to match the clustering results and become reference buildings. Because of the inability to access the indoor environment of all surveyed buildings during the field survey, it is necessary to use the questionnaire survey results, relevant literature and building design standards to simplify and apply representative floor plans to the building models.

5.4. Designs of retrofit scenarios

In this section, to obtain the results of retrofit benefits and costs, different retrofit scenarios are designed to meet the relative retrofit RIODF of the different RURB system players: the policymakers, designers and engineers, scholars and residents. Among many possible choices, retrofit measures selected for RURB scenarios in this study are supported by filtering logic based on the results of field surveys, interviews with professionals and resident questionnaire surveys. For the building index which cannot be individually acquired from the survey, secondary sources including national and local building standards and relevant literature on building façade optimisations are used as references based on their reliability (see Appendix C).

5.4.1. Library of possible retrofit measures

Quantitatively, different retrofit measures for the same retrofit criterion can achieve the same objective, but they may have differences in energy efficiency, price, the difficulty of installation and local disadvantages. Currently, it is argued that the selection of retrofit measures is dependent on the personal experience of RURB designers and engineers. For example, there are multiple choices of materials for building external wall insulation, but they have completely different insulation structures, thicknesses, prices, difficulties of construction and carbon emissions during production. Therefore, the concept of a ***library of possible retrofit measures*** should be established to help quantify and select the appropriate retrofit materials and techniques.

The library of possible retrofit measures is developed within the RURB system boundary for this study. They are also classified according to the positions where they are applied and their functionality in old residences. Their construction approaches, materials and structures are collected from the documents reviewed from BEES and RURB project reports and ordered from the cheapest to the most expensive:

1) External wall

Reflective Insulation Coating (RIC): RIC can be considered the cheapest and easiest retrofit approach to RURB. It requires only simple construction work by painting the external wall with a 5mm coat of solar heating insulation. However, thin RIC has the least thermal resistance among the many retrofit materials used for thermal insulation. Furthermore, it can be easily corroded and damaged due to the lack of protective coating since the RIC must be exposed on the outer surface of the external wall. Therefore, RIC is not very appropriate to meet the winter heating insulation demands in the HSCW zone climate conditions of the case study area.

Adhesive Polystyrene Granule Mortar (APG): APG mortar is a cheap insulation technique for the external walls of residential and rural buildings. APG is convenient during production and construction, as it is composed and mixed on-site with rubber powder, light polystyrene particles and cement, with the addition of appropriate anti-cracking fibres and various additives. It can be used on both the inner and outer surfaces of external walls. APG is proven to be an appropriate insulation approach for old buildings based on its low cost, fair fire resistance, short construction time cost and low construction difficulty.

Expanded Polystyrene Board (EPS): EPS board is the most common and popular insulation type for the retrofitting of old buildings. EPS has become a well-developed technique for external wall insulation during the last twenty years (Chen *et al.*, 2022). Its production can be completed on the factory assembly line, which has significantly reduced the industrial cost of the material. However, EPS has the weakness of lower fire prevention capacity hence it must be introduced with fireproof materials when applied to the external building surface.

Rock Wool Board (RW): RW board is a cheaper but heavier insulation technique compared to the conventional EPS board. Based on its inorganic nature, RW can reach the highest fireproof index and it has become a replacement for EPS when the fire risk of the applied surface is high. Yet RW is usually constructed from basalt or slag from the steel-making industry, hence its density is much higher than coating and polystyrene materials. Therefore, the risk of building subsidence is higher and RW is not suitable for application to the external walls of rural buildings and very old urban residences, which may not have strong building structures.

Extruded Polystyrene Board (XPS): XPS board is a more advanced insulation technique compared to conventional EPS. The average thermal conductivity of XPS is smaller than EPS, with higher thermal resistance, lower linearity and a lower expansion ratio. The closed porosity of XPS has reached 99% compared with the 80% of EPS. In this case, XPS can achieve the same thermal insulation value as EPS with up to 30% thinner structure, thus decreasing the pressure on external walls. However, per unit, XPS is 70% to 100% more expensive than EPS and can be treated as a luxurious choice during materials selection.

Polyurethane Insulation Coating (PIC): PIC is an advanced painting technique by applying polyurethane insulation coating to the external façade. Rigid polyurethane has excellent properties such as lighter weight, lower thermal conductivity and resistance to ageing and decay. PIC can be bonded with other substrates for surface protection coating and fireproof materials. However, PIC could be the most expensive insulation technique which, although widely used in developed countries in Europe, has usually been reserved for important public buildings such as natatoriums, gymnasiums and opera buildings in China. Considering the RURB purpose and local economic level of the case study area, the PIC may not be a suitable choice due to its high cost and the difficulty of the construction work involved.

2) Windows

Double-glazing windows: Double-glazed windows with an air layer between the glazing were used to replace the conventional coloured single-glazed windows with the growth in the economic level in the case study area. The field survey found that old apartments and old towers in Clusters 3 and 4 have widely used double-glazed windows and that they have become an affordable and common window type for urban residential buildings.

However, the interview results from Chapter Four showed that the window is the most important RURB measure to achieve higher energy conservation and the reduction of indoor noise problems in the HSCW climate zone. In this case, the Solar Heat Gain Coefficient (SHGC) of conventional transparent glazing is in the high range of 0.8 to 0.9 and its U-value is also high around 3.4 to 3.8. Therefore, double-glazed windows cannot satisfy the thermal performance requirement in the newest BEES for residential buildings (Chongqing Housing and Urban Rural Construction Commission, 2020) with a U-value of 2.5. Hence, they should not be considered an available retrofit measure in this study.

Low-Emissivity glazing window (Low-E): Low-emissivity glazing windows refer to a structure which has at least two insulating layers, one of air or inert gas trapped between the glazing and one of silver plating on one or both of the glass panes. Since 1990, Low-E windows have been developed as an extremely useful technique to reduce indoor solar heat gain in hot summer climates and also reduce indoor heat loss in cold winters. Moreover, the installation of Low-E windows provides high airtightness, which can significantly reduce air infiltration and noise problems compared to conventional glazed windows. With the development of production technology, double-layered Low-E windows can now be classified into two types:

- Double 6 mm layer Low-E glazing with an aluminium alloy frame, 12 mm air layer and single silver plating. Its U-value range is 2.5 to 2.8 and the SHGC of 0.3 to 0.4. This is the cheapest type of Low-E glazing in the current market and should be used in retrofit plans with very limited budgets.
- Double 6 mm layer Low-E glazing with Polyvinyl Chloride (PVC) frame, 12 mm argon gas insulation layer and double silver plating. This is the more advanced and expensive window type with a U-value range of 1.8 to 2.0 and an SHGC of 0.3 to 0.35. Following the current literature, this Low-E window type has been proven as a very appropriate passive measure to achieve high levels of energy conservation and indoor thermal comfort (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2015); (Gou et al., 2018). Yet its high cost (up to twice the price compared to the aluminium alloy frame type with an air layer and single silver plating) should also be considered to meet the affordable budget of residents.

Triple-glazing Low-E window: Triple-glazed windows with similar inert gas layers and silver plating are a window type with the best thermal resistance and solar reflection. This window type is currently the most advanced but very expensive passive measure for residential buildings and has been used in buildings located in climate zones with very cold winters. The climate conditions of this HSCW zone case study area are extremely hot summers (between 30°C to 42°C) and cold winters (between 0°C to 10°C), which makes the winter conditions less severe than in northern China (an average of -15°C). As argued by Yao *et al.* (2016), sensitivity testing of retrofit measures suggests that triple-glazed Low-E windows may cause an overheating risk in the indoor environment. Therefore, although it is the best retrofit technique in the current market, the application of this window type may not be very suitable for use in the HSCW climate zone.

3) External doors

Cold rolled galvanised steel door: This exterior door type is the most popular security door used in modern residential buildings and should be applied to replace the existing old wooden and iron doors in old urban residences. The galvanised steel door introduces an extra expanded perlite insulation layer to increase its thermal performance and further reduce air infiltration.

4) Heating and cooling equipment

Split Air Source Heat Pumps (ASHP) with split air conditioner units are stated as the most popular device for both heating and cooling in old urban residences in the HSCW climate zone, as confirmed by the field survey. The split system has the advantages of easy installation and maintenance, a cheap price and no need for an equipment room or ceiling space. As argued by Li *et al.* (2019) and Li *et al.* (2018a), the separated ASHP should be the most appropriate technique for residential cooling use in the HSCW zone. In this study, ASHP conditioners are set as the default choice in current old urban residences. The retrofit measure is to replace the old ASHP (low energy efficiency ratio, EER) with new equipment with a higher EER based on the suggested index from national BEES: GB 21455-2019 (State Administration for Market Regulation and Standardization administration, 2019) or even better equipment in the market.

Household radiator heating system (hot water): A household radiator heating system using hot water as the medium, is an effective, advanced technique for winter heating supply. A radiator heating system uses energy from natural gas to generate hot water and pumps the water flow around the rooms. Historically, it was a very luxurious winter heating strategy in China before the 21st century (National Development and Reform Commission, 1996), but it has been widely used in developed countries in Europe, the United Kingdom and the United States.

It is argued that the radiator system can reduce energy consumption and carbon emissions by using a primary resource since the ASHP for winter heating uses a secondary resource: electricity. Furthermore, the radiator system provides more radiant heating than convective heating, which is proven by thermal comfort research to be much more comfortable for indoor occupants (Du et al. (2022): Su et al. (2018); Hu et al. (2016). Therefore, the radiator heating system in this study is considered a retrofit measure with benefits for both energy conservation and comfort improvement. It is suitable only for residents who can afford the cost.

Central cooling system: Central cooling systems including Variable Air Volume Systems (VAV), Variable Refrigerant Volume Systems (VRV) and fan coil unit systems, have been widely used for the summer cooling of public and residential buildings in the United States (Alexander *et al.*, 2017). These systems require an additional indoor room for the central machine and equipment and sufficient ceiling height for diffusers. Since the total indoor area of this study was defined as 60 and 120m^2, central cooling systems are argued as too expensive and space-consuming to be introduced to the old urban residences in the case study area. Moreover, concerns about centralised cooling systems have been widely argued recently as helping the spread of airborne diseases such as Covid-19 pneumonia (Yan *et al.*, 2022). Hence these central cooling systems may not be appropriate RURB measures for the case study area.

District heating systems: District heating systems are unique centralised systems used in the SC & C climate zones in northern China. They require central heating stations to be built in an urban area. They supply hot water to surrounding residences through underground pipes by burning coal as the main resource. This system has been widely critiqued because of its air pollution and energy waste problems (Tsinghua University Building Energy Research Center, 2021). It could be seen as a historical engineering legacy during the national development (FinancePeople.com, 2014). Following the statement from experts Jiang (2021), applying the district-heating system in southern China is unsustainable and unreasonable due to the extremely high cost of construction and the relatively low heating intensity requirement in the HSCW and HSWW climates. Therefore, the district-heating system is not considered a possible retrofit technique in the HSCW climate zone.

5) Other passive energy efficiency measures

Air tightness: Following the ASHRAE standard of indoor thermal comfort and ventilation, air tightness is one of the most important problems for energy consumption and thermal comfort in old buildings, quantified as the air infiltration rate to represent the air exchange between the indoor and outdoor environments. For the RURB process, airtightness can be improved by replacing old, cracked windows and external doors with new, insulated, Low-E windows and thick security doors. Meanwhile, it is possible and necessary to seal the existing holes on the old external walls used by the old air conditioners.

Inner window shading: The climate conditions in the case study HSCW zone bring extremely hot summers with high solar radiation heat gain. The sunshade device is a means of reducing indoor heat gain to reduce the cooling load requirement in the summertime. In this case, a Venetian blind is a possible low-cost, easily installed measure. Although most old urban residences have installed opaque curtains on windows, an additional Venetian blind can provide more flexible control of sunlight to satisfy the indoor lighting demand compared to the fixed shelter area from curtains.

Styrene-Butadiene-Styrene (SBS) waterproof asphalt roll: The SBS asphalt rolls are widely used specifically for the retrofitting of building roofs. The old urban residences usually have flat rather than sloping roofs, which have problematic potential in rainwater deposition, as well as relevant issues of corrosion, leakage and the hot or cold bridge effect on the roof structure. In this case, SBS asphalt rolls are usually combined with thermal insulation layers such as EPS and XPS boards during the roof retrofitting process to further increase the thermal, waterproof and tightness performance.

6) Air quality

Mechanical ventilation system: The centralised mechanical ventilation system has been widely used in public and modern apartment buildings in developed countries. This system is very effective for controlling indoor air quality through the supply of purified fresh air. It can also heat the fresh air by using waste heat from the return air to further increase energy efficiency. However, similar to the central cooling system, the mechanical ventilation system has the same problems of high cost and the need for an air duct, ceiling space and equipment rooms. Based on the limited space in old urban residences, this centralised technique may not be suitable for RURB.

Air purifier: An indoor air purifier is a split technique to improve indoor air quality. Air purifiers have the advantages of being cheap, easy to install, easy to move around the rooms and not needing ceiling space compared with the duct-based ventilation system (Ito and Zhang, 2020). With the development of air purifier technology, this split system has been widely tested and proven by scholars such as Lu *et al.* (2019) to have an increased ability and efficiency to clean indoor air of pollution and particles. Specifically, in the HSCW climate zone, the fresh-air natural ventilation through occupant operation of windows has proved to be the most popular approach to adjusting thermal feelings, as well as being an energy-efficient technique (Yao et al. (2009); Li et al. (2015); D'Oca and Hong (2014). Therefore, the split air purifier system might be more appropriate to meet the conditions of the case study RURB.

7) Lifts

Outdoor lift: The installation of lifts in old urban residences has been identified as the retrofit measure with the highest priority, interest and importance from the survey result. A lift can significantly increase the accessibility of old residences, as well as the functionality and living quality of the residents. Since the old urban residences have no space available for constructing lift shafts inside of buildings, an outdoor lift is the only option (see Figure 5.10). Considering the natural lighting and noise issues that are argued to be problems caused by lifts, the lift shafts should be constructed using glass curtains, and sound-insulating materials and kept at a reasonable distance clear of the building.

Figure 5.10: Outdoor lift installation, design diagram and example

8) Safety

Based on the RURB system boundary defined for the case study, the green space, public facilities of convenience and entertainment, car park space and fire access space are not considered due to the limited outdoor floor space. On the other hand, the lighting system in public spaces inside the old residential buildings and the indoor fire alarm devices can still be possible retrofit measures to increase residents' safety.

Public space lighting: From the field survey, a significant problem is the lack of sufficient lighting found in public spaces, especially in the building entrance, staircase and corridors of dilapidated apartments (see Figure 5.11 as problems discovered from the field survey). Since the majority of these very old urban residences have no lift, residents must walk through a very dark passageway to their home doors, which is a dangerous risk in the evening for elderly people. By installing solar energy or battery LED lamps on the ceiling of these public spaces, this safety problem can be easily settled with very low cost and energy consumption.

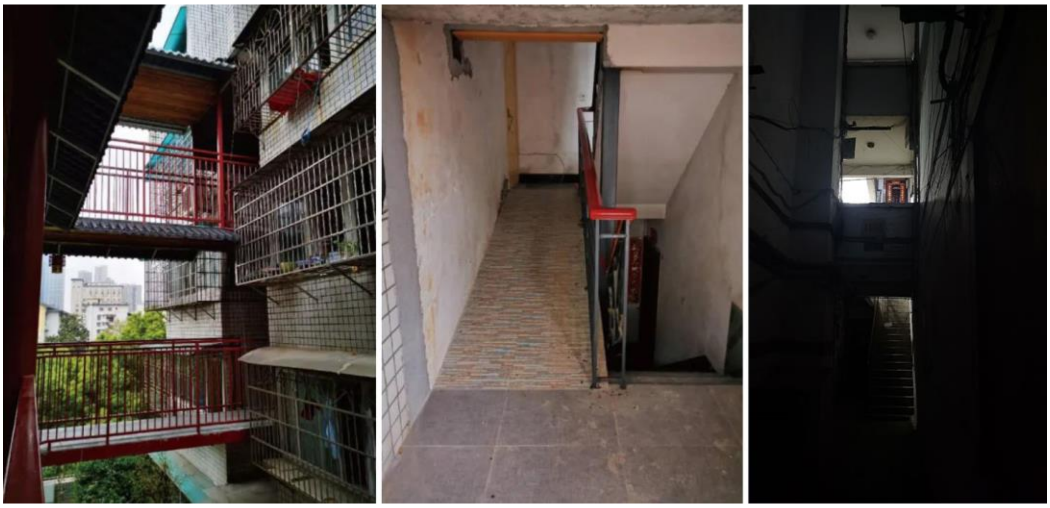


Figure 5.11: The discovered problem of 'lack of lift and public space lighting' from the field survey

Indoor smoke detector: From the results of both the interview and field survey, all the old urban residences in the case study have no indoor smoke detectors installed for fire alarms. Since more and more electronic devices - HVAC and plug-ins - due to the improvements in economic level, the fire risks of old urban residences may have also increased. Therefore, indoor smoke detectors for bathrooms, living rooms and bedrooms should be considered as a necessary measure to be applied during the retrofit process. In the current market, the technology of indoor smoke detectors has been rapidly developed, the production is very cheap, the installation work is very convenient (simply pasting to the ceilings with no need for drilling) and the battery life of a single detector can last for 10 years.

5.4.2. Global limit and degree limit for RURB design

Furthermore, since the final retrofit plan must be affordable and reasonable to meet the retrofit demands of RURB system players, it is necessary to introduce the concept of **global limit and degree limit** during the selection of retrofit measures and to further classify RURB scenarios, based on the RIODF results from CLD analysis.

1) Global limit

Global limit is a means of judgement while selecting the retrofit measures from the library. This limit is set based on the survey results, the minimum value of building retrofit standards and the initiative of control system players. The global limit is the principle that identifies the rationality of the selected technique.

For example, the questionnaire survey has collected the maximum affordability of retrofit cost and time, so the total economic and time cost of the selected retrofit techniques cannot exceed this global limit. Meanwhile, since residents cannot retrofit the external walls of old apartment buildings, the global limit of the RSR model from CLD should not consider the techniques for a building's external façade. Similarly, the city government cannot access the private indoor environment to retrofit windows and HVAC devices, so the GDR model from CLD has its global limit to avoid intruding into households.

2) Degree limit

Quantitatively, in the library of available retrofit measures, different techniques and materials may achieve the same objective, but with many variations in the price and/or installation difficulty. Therefore, the degree limit is set to control the budget for retrofit techniques that can achieve the same retrofit objectives but with different cost performances.

For example, adhesive polystyrene granule mortar (APG), expanded polystyrene board sheets (EPS) and polyurethane insulation coating (PIC) are three possible retrofit measures applied to building external walls, but PIC is much more expensive and hardly used on residential buildings; APG is cheaper and requires less construction time, but produces a worse aesthetic surface; EPS is frequently used for building retrofit with mature engineering technology and lower total quality of materials. In this case, the degree limit is introduced into each RURB scenario based on the limit of the retrofit cost, as frugal or luxurious packages, for which quantitative information can also be collected from the resident questionnaire survey.

Combining the three concepts of the library of possible retrofit measures, global limit and degree limit, the selection of retrofit measures can be developed as a filtering logic shown in Figure 5.12:

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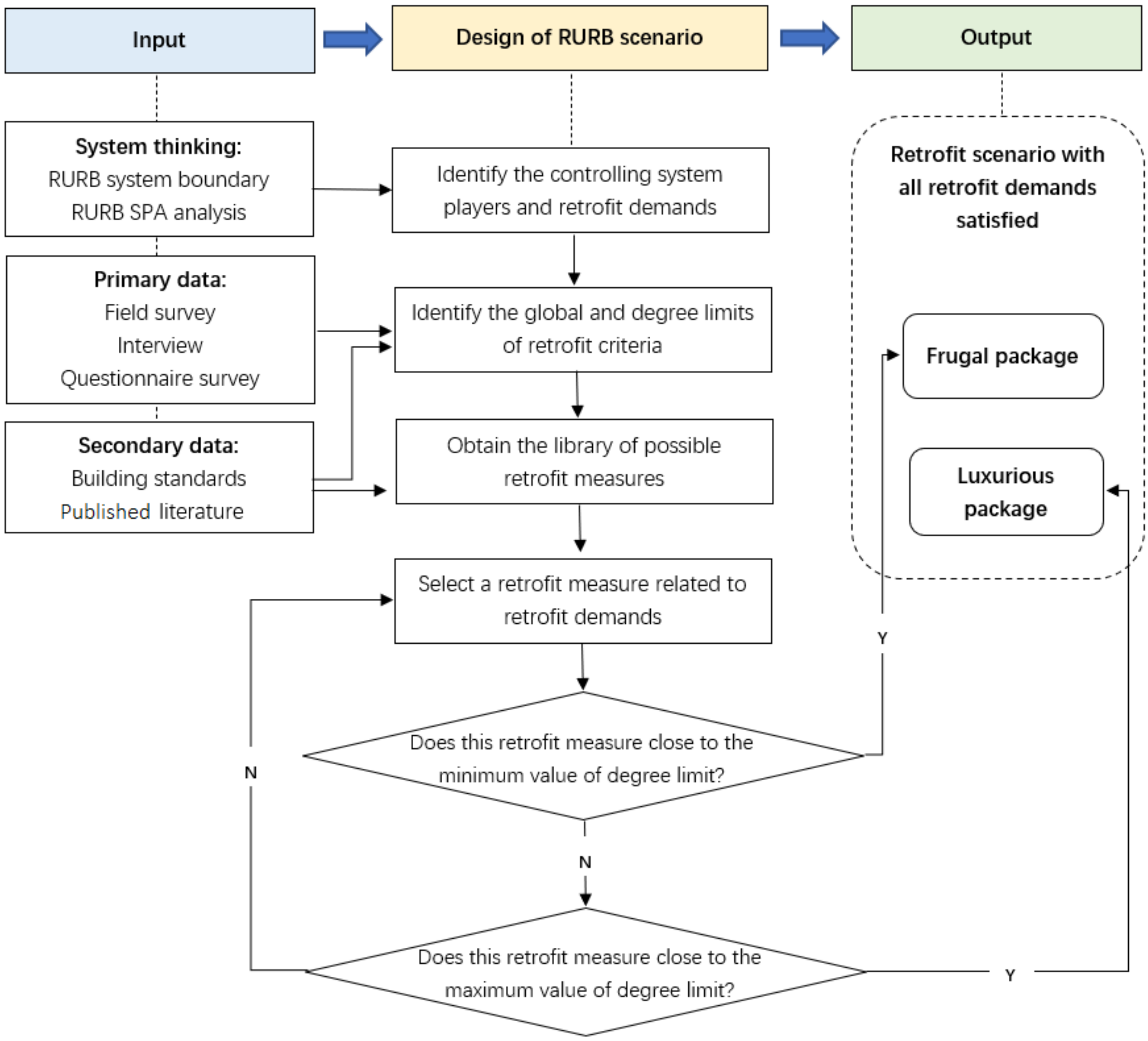

Figure 5.12: Filtering logic for the retrofit scenario design and the selection of retrofit measures

By proceeding with this filtering logic based on developed RURB system interactions of CLD, the final packages of selected retrofit measures are aggregated to form retrofit scenarios.

5.4.3. Baseline scenario and constant parameters

The baseline scenario is designed to describe the current building conditions based on old building regulations and the field survey results. Moreover, constant settings including occupancy behaviour, thermal comfort requirements, lighting, indoor heat gain and equipment energy are not changed in different retrofit scenarios. In this study, the indoor air temperature range is strictly limited to the 18°C to 26°C comfort zone based on the lowest requirement in the thermal comfort building standard. Two types of household plans (60m^2 and 100m^2), the occupancy behaviour profiles, two types of family structures (3 and 5 people) and the heating season data are used from the resources of building standards for residential buildings GB 50096 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2012a), social survey results, and the literature on behavioural studies of the same case study area from Jiang *et al.* (2020), Cao et al. (2021) and Li *et al.* (2018b). Two typical plans of households used for residence modelling are shown in Figure 5.13:

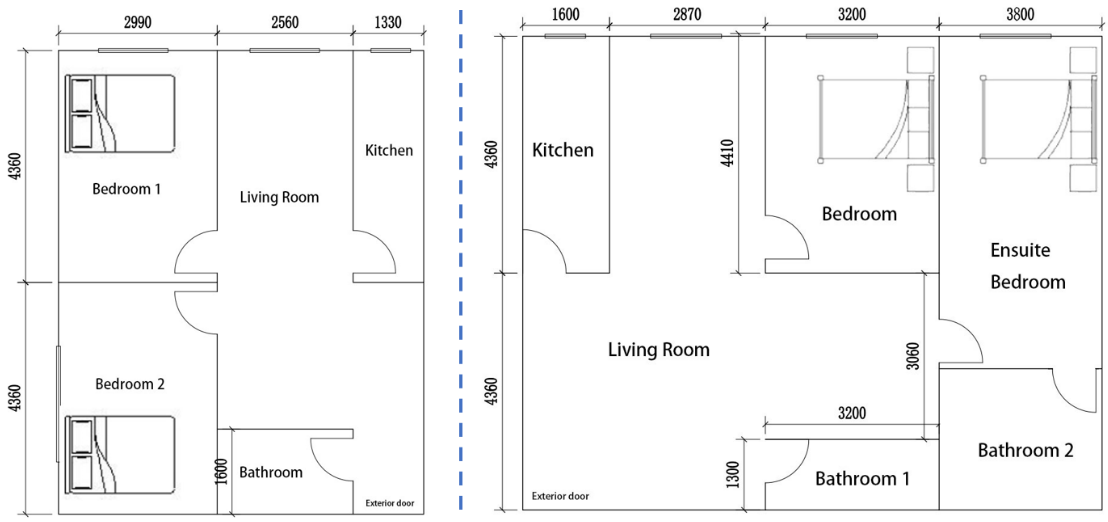

Figure 5.13: Two typical household plans for building modelling

A summary of baseline scenario settings for building conditions is shown in Table 5.3:

Table 5.3: Summary of baseline scenario settings for case study RURB

Content		Unit	Cluster 1 Value	Cluster 2 Value	Cluster 3 Value	Cluster 4 Value
Basic info.	◆ Floor number	floor	6	8	10	30
	◆ Floor height	m	2.8	3	3	3
	◆ External wall area (total)	m^2	1036	2489	3937	7816
	◆ External window area (total)	m^2	233	590	977	3370
	◆ Window-to-wall ratio		0.18	0.19	0.20	0.30
	◆ Roof area	m^2	357	799	1042	805
	◆ Household number (total)	family	24	64	120	240
	◆ Resident number (total)	people	64	256	440	960
	◆ Residential area (total)	m2	1920	5120	8800	19200

External wall, floor	◆ Cement mortar 20mm ◆ Sand-lime brick 240mm ◆ Cement mortar 20mm	U-value	2.43	2.43	/	/
	◆ Cement mortar 20mm ◆ Solid clay brick 240mm ◆ Cement mortar 20mm	U-value	/	/	2.03	/
	◆ Crack-resistant mortar 20mm ◆ Reinforced concrete shear wall 200mm ◆ Lime mortar 20mm	U-value	/	/	/	3.21
Roof	◆ Cement mortar 20mm ◆ Cement cinder 60mm ◆ Reinforced concrete shear roof 120mm ◆ Cement mortar 20mm	U-value	2.80	2.80	2.80	2.80
Window	◆ Coloured single glazing ◆ (SHGC=0.65)	U-value	6.33	6.33	/	/
	◆ Single glazing ◆ (SHGC=0.89)	U-value	/	/	6.33	/
	◆ Double glazing 6mm air ◆ (SHGC=0.81)	U-value	/	/	/	3.63
External door	◆ Aluminium alloy door	U-value	2.80	2.80	/	/
	◆ Galvanised steel door	U-value	/	/	1.76	1.76
HVAC	◆ Air infiltration	ac/h	1.5	1.5	1	1
	◆ Split air conditioner	EER	2.8	2.8	2.8	2.8
		COP	2.2	2.2	2.2	2.2
Lift	◆ Lift installation		None	None	None	Yes
Safety	◆ Public space lighting		None	None	Poor	Poor
	◆ Indoor smoke detector		None	None	None	None

The summary of baseline scenario settings for occupancy behaviour is shown in Table 5.4 to represent the schedule of the in-building ratio. The household of 60m^2 indoor area contains two middle-aged office workers and one young student. The household plan with a 100m^2 indoor area is designed with an additional two elderly retired residents. The indoor occupancy profile is set to the most adverse conditions of energy use – elderly people will stay indoors throughout the day and other people will stay indoors during the weekend

Table 5.4: Occupancy behaviour profile

Household plan: 60 m^2 (3 people)						Household plan: 100 m^2 (5 people)					
		Weekdays		Weekends				Weekdays		Weekends	
Room	Time	People	Lighting & device	People	Lighting & device	Room	Time	People	Lighting & device	People	Lighting & device
Bedroom 1	0:00-7:00	2		2		Ensuite bedroom	0:00-7:00	3		3	

	7:00-8:00			2			7:00-8:00			3	
	8:00-9:00			2			8:00-9:00			3	
	13:00-15:00			2	Device on		13:00-15:00			3	Device on
	22:00-24:00	2	Both on	2	Both on		22:00-24:00	3	Both on	3	Both on
Bedroom 2	0:00-7:00	1		1		Bedroom	0:00-7:00	2		2	
	7:00-8:00			1			7:00-8:00	2		2	
	8:00-9:00			1			8:00-9:00	2		2	
	13:00-15:00			1	Device on		13:00-15:00	2	Device on	2	Device on
	22:00-24:00	1	Both on	1	Both on		22:00-24:00	2	Both on	2	Both on
Living room	7:00-8:00	3	Device on			Living room	7:00-8:00	5	Device on		
	8:00-9:00						8:00-9:00	2	Device on		
	9:00-13:00			3	Device on		9:00-13:00	2	Device on	5	Device on
	15:00-17:00			3	Device on		15:00-17:00	2	Device on	5	Device on
	17:00-22:00	3	Both on	3	Both on		17:00-22:00	5	Both on	5	Both on

Significantly, occupancy behaviours, clothing insulation, domestic hot water, lighting and internal heat gain should also be considered as constant parameters rather than variables, because it is impossible to acquire the individual clothing situation, light bulb types and numbers and indoor functional equipment types and usage from every household unit. Considering the nature of old buildings for retrofit studies, there are no extremely luxurious lighting bulbs and electronic equipment. Therefore, the minimum average illumination and internal heat gain data provided by the residential building standard (see Appendix C for all standards reviewed) are selected and applied to all scenarios and building types as two constant values. Their usage schedules are the same as occupant profiles.

The constant indoor index of the baseline scenario is summarised in Table 5.5:

Table 5.5: Constant index for all scenarios

Name	Index	Control method	Note
Weather condition	Shapingba district, Chongqing City, China		
Window size	1500 x 1800 (mm)	Bedrooms 1, and 2, living room	Windows of apartment

	900 x 900 (mm)	Kitchen & restroom	buildings
	3000 x 1800 (mm)	Ensuite bedroom, bedroom	Windows of tower buildings
	2100 x 1800 (mm)	Bedrooms 1, 2, living room	
	1200 x 900 (mm)	Kitchen & restrooms	
External door size	2000 x 1000 (mm)		
Heating temperature	26°C	When the outdoor temperature is lower	Use natural ventilation if possible
Heating season	1st November to 1st March (the following year)		
Cooling temperature	18°C	When the outdoor temperature is higher	Use natural ventilation if possible
Cooling season	1st May to 1st October		
Natural ventilation		Through windows	Has constant infiltration
Occupancy heat gain	70.0 W/m^2	Follow occupancy behaviour	-
Lighting power	6 W/m^2	Follow occupancy behaviour	-
Equipment power	4.3 W/m^2	Follow occupancy behaviour	-
Domestic hot water	30L / person • day	Boiler efficiency: 95% (natural gas)	Use 60° C water for calculation, the cost of water is not considered

5.4.4. Resident Spontaneously Retrofit scenario (RSR)

Following the system interaction results from CLD, the RSR model is designed and limited based on the interview and questionnaire survey results. It shows the packages of retrofit measure preferences from residents only, who may not have enough built environment knowledge.

The retrofit demands and limits of the RSR scenario are summarised in Table 5.6:

Table 5.6: Retrofit demands and limits of RSR scenario design

	Content	Source
Retrofit demands	◆ To improve indoor thermal comfort, functions, and safety	Q34
	◆ To increase the living quality and indoor health environment	Q34
	◆ To reduce the energy bills	Q34
	◆ To increase the house value	Q34
	◆ Replacement of old and low energy-efficient HVAC devices	Q19
	◆ Increase the usage of HVAC and air quality devices	Q15

	◆ Replacement of windows and external doors	Q16, Q18, Q28
	◆ Add lift insulation to improve accessibility by coordinating the whole building	Interview
	◆ Add indoor smoke detectors for fire safety	Interview
Global limit	◆ Residents **cannot** proceed retrofit of external walls of apartment and tower buildings	Interview
Degree limit	◆ Residents **cannot** proceed retrofit of apartment and tower building roofs	Interview
	◆ Residents **cannot** proceed retrofit of public space lighting	Interview
	◆ The majority of residents state the affordable retrofit cost as ￥50,000	Q22
	◆ The maximum retrofit money cost should not be over ￥100,000	Q22
	◆ The maximum retrofit time cost should not be over 2 months	Q24

With the principle of global and degree limits, the RSR model can be classified into two scenarios based on the residents' retrofit budget and the complexity of retrofit measures:

1) **RSR-a** (Frugal): The economic level of households is limited. Only old external windows and HVAC equipment are replaced with new, but affordable, cheaper ones. The selected retrofit measures from the library are aggregated as a package applied on three sectors: external windows, heating and cooling equipment, as shown in Table 5.7.

Table 5.7: RSR-a scenario settings with selected retrofit measures

		Cluster 1	Cluster 2	Cluster 3	Cluster 4
External window	Retrofit measure	Low-E double-layer insulating glass 6+12+6, aluminium alloy window frame			
	Value	U-value = 2.60, SHGC = 0.33			
Heating and cooling	Retrofit measure	Replacement of old equipment: split air conditioner			
	Value	Equipment EER* = 3.2, COP* = 2.6			
Note: EER refers to the energy efficiency ratio for cooling, COP refers to the coefficient of performance for heating					

2) **The RSR-b** (Luxurious): This scenario is designed to retrofit as much as residents can to improve energy efficiency and the indoor built environment. There are more retrofit techniques introduced by residents themselves, including windows, external doors, heating and cooling equipment, air purifier, inner shading blind, lift

and indoor smoke detectors. In this case, more retrofit measures are selected from the library, which can be achieved without too complicated construction works, see Table 5.8:

Table 5.8: RSR-b scenario settings with selected retrofit measures

		Cluster 1	Cluster 2	Cluster 3	Cluster 4
External window	Retrofit	Low-E double-layer insulating glass 6+12+6, PVC window frame			
	Value	U-value = 1.88, SHGC = 0.33			
External door	Retrofit	Galvanised steel anti-theft door (expanded perlite insulation layer)			
	Value	U-value = 1.76, air infiltration rate reduced by 0.5			
Heating	Retrofit	Radiator heating system (family unit with natural gas boiler)			
	Value	Boiler efficiency = 99%			
Cooling	Retrofit	Replacement of old equipment: split air conditioner			
	Value	EER = 3.2, COP = 2.6			
Air quality	New	Air purifier (single unit, power = 60W)			
Shading	New	Venetian blind (solar radiation intensity control)			
Lift		Add one outdoor lift (raise funds)			None
	Number	1	1	2	-
Fire safety	New	Indoor smoke detector (battery)			

5.4.5. Government-Driven Retrofit scenario (GDR)

The GDR model refers to another isolated scenario in which the local government is the main driving force of RURB based on their governmental objectives. In this case, the residents' opinions and preferences are neglected and they do not need to pay anything for the retrofit cost, but the government will drive the retrofit construction work all by itself, following mandatory rules from the newest residential building design standards. The retrofit demands and limits of the GDR scenario are summarised below in Table 5.9:

Table 5.9: Retrofit demands and limits of GDR scenario design

	Content
Retrofit demands	◆ To reduce urban building energy consumption and carbon emission due to national objective ◆ To improve residents' living quality and happiness ◆ To improve the city's scenic and artistic landscape ◆ To obtain political achievements ◆ Provide construction team to design and retrofit external walls and roofs ◆ Add, repair and replace old, poor, public space lighting ◆ Provide a governmental subsidy to residents who apply energy efficiency retrofit measures, as motivation ◆ Provide governmental subsidy as a discount for energy-efficient HVAC equipment to attract purchase intentions

Global limit	◆	The maximum retrofit time cost should not be over 2 months
	◆	The government **cannot** directly proceed retrofit of HVAC equipment, other indoor devices and lifts
	◆	The government-driven retrofit of the building façade should have its index meet the minimum requirement of the current new building standard
Degree limit	◆	The average retrofit subsidy of new lift installation in the case study urban area
	◆	The average discount for purchasing new equipment (such as air-conditioners) in the case study city
	◆	Supporting the structural strength of old residences increases the retrofit difficulty and limits possible retrofit measures

Different administrative regions may have completely different economic levels – which affects the available governmental budget for RURB for each urban zone. Therefore, the GDR model is also classified into two sub-scenarios due to the limitation of the available governmental budget.

1) **GDR-a** (subsidy only): The economy and potential governmental action are limited. The government cannot directly participate in the retrofit construction works. In this case, only limited subsidies and price discounts are provided for residents to purchase new windows and HVAC equipment in the RSR-a scenario.

   In this model, the retrofit measures applied are the same as the RSR-a model and the government can provide a minimum subsidy of 25 Chinese Yuan (CNY) per m^2 of the residential area and 400CNY for each new air conditioner purchased.

2) **GDR-b** (external façade covered): The government can directly carry out retrofit construction works on building external walls and roofs. The government will pay and contract all labour and material to promote the external building façade to the minimum requirement of the newest mandatory building standards. In this case, the residents just receive the retrofit benefits for free and do not need to pay or do anything. The GDR-b model can be in extreme contrast to GDR-a.

   This scenario shows the government has a strong economy and the ability to contract labour and materials for wall and roof retrofit. The relevant U-value requirements are set in the index of the current national building standard in the same city of JGJ 134-2010 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2010b) and DBJ 50-071-2020 (Chongqing Housing and Urban Rural Construction Commission, 2020), as shown in Table 5.10. Residents have no burden and do not have to pay for retrofit. In this case, residents and policymakers are still isolated, so the indoor built environments are not considered by the government.

Table 5.10: GDR-b scenario settings with selected retrofit measures

		Cluster 1	Cluster 2	Cluster 3	Cluster 4
External wall	Retrofit	Cement mortar 20mm APG 50mm Crack-resistant mortar 20mm			Cement mortar 20mm EPS Board 40mm Crack-resistant mortar 20mm
	Value	U-value = 0.79			U-value = 0.78
Roof	Retrofit	Cement mortar 20mm XPS Board 40mm SBS asphalt waterproof rolls 5mm Cement mortar 20mm			
	Value	U-value = 0.54			
Public space lighting		Add, repair, and replace old bulbs with LED bulbs for each floor			

5.4.6. Cooperative Retrofit scenario (CR)

The Cooperative Retrofit (CR) model presents an ideal retrofit mode in which four RURB system players cooperate and are linked together by causal loops and feedback. Following the RIODF from the CLD-CR results in Chapter Four, the system players are no longer isolated and they have their subjective initiative and inputs to the ideal CR model.

- From the perspective of residents living in old urban residences, the government can provide top-down administrative help and take the responsibility to retrofit external walls, roofs and public space lighting for shared building space, so residents can focus on the indoor retrofitting of windows, doors, heating, cooling and air quality devices. They may also be encouraged with benefits for deciding to retrofit through various discount prices for both devices and energy bills.
- In the view of the government, they will lead and pay for the construction team for the building façade retrofit and they can also provide governmental subsidies (in the form of purchase discounts, energy bill prices and one-off subsidies) to encourage the application and retrofit measures with the purpose of energy conservation (such as devices with a high energy efficiency coefficient) and

functionality improvement (such as lifts).

- Scholars of RURB can provide scientific directions and guidance on building façade parameters (including material structure, thickness, heat resistance and fireproof performance), cost performance, energy efficiency coefficients, thermal performance and the local applicability of retrofit measures. For example, residents can obtain scientific suggestions from scholars during the purchase of heating, cooling, air quality and hot-water devices. Furthermore, scholars can develop new retrofit technologies, materials and devices to further increase the energy conservation and comfort improvements of RURB.
- The RURB designers and engineers led by residents or the government can also be guided by scholars to design and apply the most appropriate retrofit measures for building façades suitable for the local climate and building conditions (in the form of updating old BEES supported by scholars).

In the CR model, the cooperation between residents and the government can break the barrier caused by the global limits in the RSR and GDR models. The retrofit of both indoor and outdoor building spaces can proceed at the same time. Similarly, the CR model can be further classified into two retrofit scenarios based on the differences in degree limit:

1) CR-a: The degree limit of the CR-a scenario is shown as the limited retrofit budget both from residents and local government. The retrofit measures selected for CR-a aim to provide the minimum requirement of the newest current BEES for residential buildings. It is shown as a combination of the RSR-a scenario and GDR-b scenario to increase the thermal performance of the building façade, the energy efficiency of HVAC equipment and qualitative improvements for accessibility and safety, with additional retrofit techniques for indoor shading.

Table 5.11: CR-a scenario settings with selected retrofit measures

		Cluster 1	Cluster 2	Cluster 3	Cluster 4
External wall	Retrofit	Cement mortar 20mm APGC 50mm Crack-resistant mortar 20mm			Cement mortar 20mm EPS Board 40mm Crack-resistant mortar 20mm
	Value	U-value = 0.79			U-value = 0.78
Roof	Retrofit	Cement mortar 20mm			

		XPS Board 40mm SBS asphalt waterproof rolls 5mm Cement mortar 20mm			
	Value	U-value = 0.54			
External window	Retrofit	Low-E double-layer insulating glass 6+12+6, aluminium alloy window frame			
	Value	U-value = 2.60, SHGC = 0.33			
Heating and cooling	Retrofit	Replacement of old equipment: split air conditioner			
	Value	EER = 3.2, COP = 2.6			
Shading	New	Venetian blind (solar radiation intensity control)			
Lift	New	Add one outdoor lift (raise funds)			None
	Number	1	1	2	-
Public space lighting		Add, repair, and replace old bulbs with LED bulbs for each floor			

2) CR-b: The CR-b scenario is set as the ideal retrofit model for a strong retrofit desire, adequate budget and scientific suggestions from all RURB system players: residents, designers and engineers, scholars and policymakers.

   The ideal CR-b model selects the very advanced retrofit techniques and materials for the most appropriate thermal performance of the building façade adapted to the local climate conditions (referenced from published research). The improvements in building façade and built environment quality are maximised by introducing more comfortable HVAC equipment including Low-E windows, radiator heating systems, air purifiers, shading blinds and smoke detectors. Meanwhile, the government will contribute to comprehensively retrofitting walls, roofs and public space lighting, as well as providing extensive subsidies for energy-efficient HVAC equipment and lift installation. Consequently, the CR-b scenario is the best retrofit design in this study, which presents the connected system players expressing their unique, individual knowledge and RIODF for the RURB system.

Table 5.12: CR-b scenario settings with selected retrofit measures

		Cluster 1	Cluster 2	Cluster 3	Cluster 4
External wall	Retrofit	Cement mortar 20mm XPS Board 40mm Crack-resistant mortar 20mm			
	Value	U-value = 0.79			U-value = 0.78
Roof	Retrofit	Cement mortar 20mm XPS Board 40mm SBS asphalt waterproof rolls 5mm			

	Value	Cement mortar 20mm U-value = 0.54			
External window	Retrofit Value	Low-E double-layer insulating glass 6+12+6, PVC window frame U-value = 1.88, SHGC = 0.33			
External door	Retrofit Value	Galvanised steel anti-theft door (expanded perlite insulation layer) U-value = 1.76, air infiltration rate reduced by 0.5			
Heating	Retrofit Value	Radiator heating system (family unit with natural gas boiler) Boiler efficiency = 99%			
Cooling	Retrofit Value	Replacement of old equipment: split air conditioner EER = 3.6, COP = 3.0			
Air quality	New	Air purifier (single unit, power = 60W)			
Shading	New	Venetian blind (solar radiation intensity control)			
Lift	New Number	Add one outdoor lift (raise funds) 1	 1	 2	None -
Public space lighting		Add, repair, and replace old bulbs with LED bulbs for each floor			
Fire safety	New	Indoor smoke detector (battery)			

5.5. Building energy simulation

Following the 'before-retrofit stage' presented above, this section presents the 'after-retrofit stage', by applying Building Energy Modelling (BEM) to simulate the retrofit process of designed scenarios. The gap between retrofit benefits and costs is summarised as retrofit criteria – they are calculated and analysed as quantitative results of energy, economic cost and time cost, as well as the qualitative results for indoor comfort, functionality and safety.

To relieve the conflicts between the three retrofit scenarios which represent the retrofit demands of the four RURB players, it is necessary to evaluate and decide the best scenario by using Multi-Criteria Decision-making (MCDM) analysis. After reviewing the MCDM analysis methods, the Analytic Network Process (ANP) method was selected to evaluate the RURB scenarios according to the results of the retrofit criteria. The chosen scenario is the best retrofit package to satisfy all the RIODF characteristics of the RURB system players.

In this study, the RURB process is conducted through the BEM computer simulation method due to the urban scale of the research and the large number of buildings. The BEM software exports the results of the energy consumption data based on imported retrofit scenarios, as explained below.

5.5.1. Software used for RURB modelling and simulation

Three computer software programs related to BEM are selected for the RURB simulation process:

SketchUp and **OpenStudio**: OpenStudio was developed by the United States National Renewable Energy Laboratory. It is an add-on of the architectural SketchUp drawing software to provide an integrated, visual, user interface for the EnergyPlus, CONTAM airflow and Radiance engines. OpenStudio uses SketchUp to build 3D geometric models (Office of Energy Efficiency & Renewable Energy, 2014). OpenStudio is very suitable for architects and building, energy and environmental engineers to dramatically reduce the effort required to build and maintain BEM models. Users can clearly and conveniently build a visual, geometric, building model for EnergyPlus simulation. In this study, the OpenStudio kit version 3.3.0 is introduced into the SketchUp software version 2017 to reduce the tedious modelling effort involved in constructing models and indoor thermal zone settings, as in Figure 6.1.

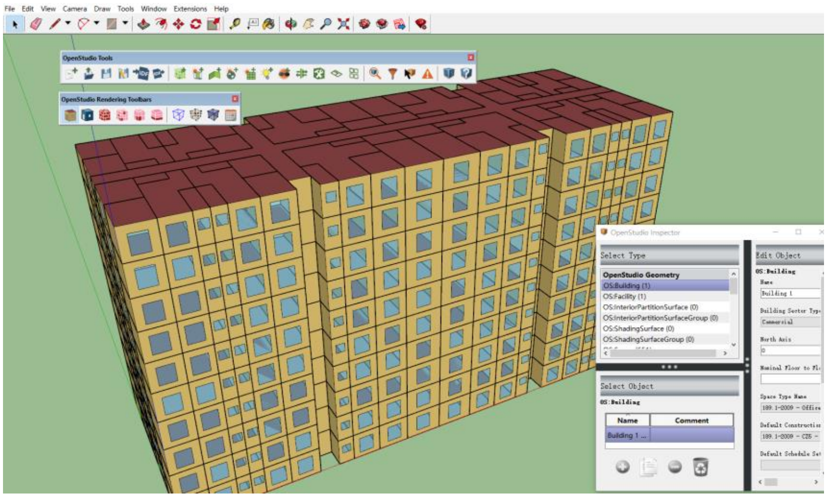

Figure 5.14: The SketchUp software and OpenStudio Plug-in interface for RURB modelling

EnergyPlus (E+): the EnergyPlus engine was developed by the Department of Energy of the United States and the Lawrence Berkeley National Laboratory for BEM. It is an open-source program that engineers, architects and researchers use to simulate building operating energy consumption, including heating, cooling, ventilation, lighting, plug-in energy, water use and domestic hot water in buildings. It is a widely-used software for building energy simulations. Its ability and effectiveness in dynamically acquiring indoor energy data have been widely proven by academic research.

In this study, EnergyPlus version 9.6.0 is applied for the RURB simulation process for the retrofit scenarios designed in Chapter Five. The documentation files provided by the EnergyPlus official website were used during the importing and exporting processes. The documentation 'EnergyPlus essentials' was used when learning the software and the principles of operation; the 'engineering reference' was followed when modelling the HVAC system and the 'input and output reference' was used to model the retrofit scenarios and generate the retrofit results data.

5.5.2. Result of Annual Operating Energy Consumption Intensity (OECI)

The building models and retrofit scenarios imported into the building energy modelling process are indicated above in section 5.4 as one baseline scenario and six retrofit scenarios – each of which is multiplied by four clustered building types to give a total of 28 different models. Considering the three factors: 1) quantitative retrofit results for energy efficiency; 2) qualitative results for comfort, accessibility and safety improvements and 3) the constant parameters of lighting, indoor plug-in energy and domestic hot water energy, the OECI should be classified into two similar types: 1.) the HVAC equipment and 2.) other energy devices The exported results for the annual OECI from the BEM simulation process are shown in Table 5.13 and Figure 5.15:

Table 5.13: Annual OECI data exported from the BEM simulation process. Unit: kWh per $m^2 \cdot$ year

Retrofit scenarios		**Cluster 1 (6F): Dilapidated Apartment**	**Cluster 2 (8F): Dilapidated Apartment**	**Cluster 3 (10F): Old apartment**	**Cluster 4 (30F): Old tower**
Baseline	HVAC	195.2	195.7	146.0	143.3
	Total	244.8	245.2	193.5	192.9
RSR-a	HVAC	142.6	136.9	127.7	125.9
	Total	192.2	186.4	175.2	175.5
RSR-b	HVAC	45.0	43.2	38.3	44.9
	Total	119.1	116.7	112.5	115.3
GDR-a	HVAC	142.6	136.9	127.7	125.9
	Total	192.2	186.4	175.2	175.5
GDR-b	HVAC	138.3	146.5	108.6	101.2
	Total	187.8	196.0	156.1	150.8

CR-a	HVAC	87.3	89.6	90.1	83.7
	Total	140.5	142.3	141.5	133.2
CR-b	HVAC	26.8	24.3	23.8	26.8
	Total	100.8	97.9	98.0	97.2

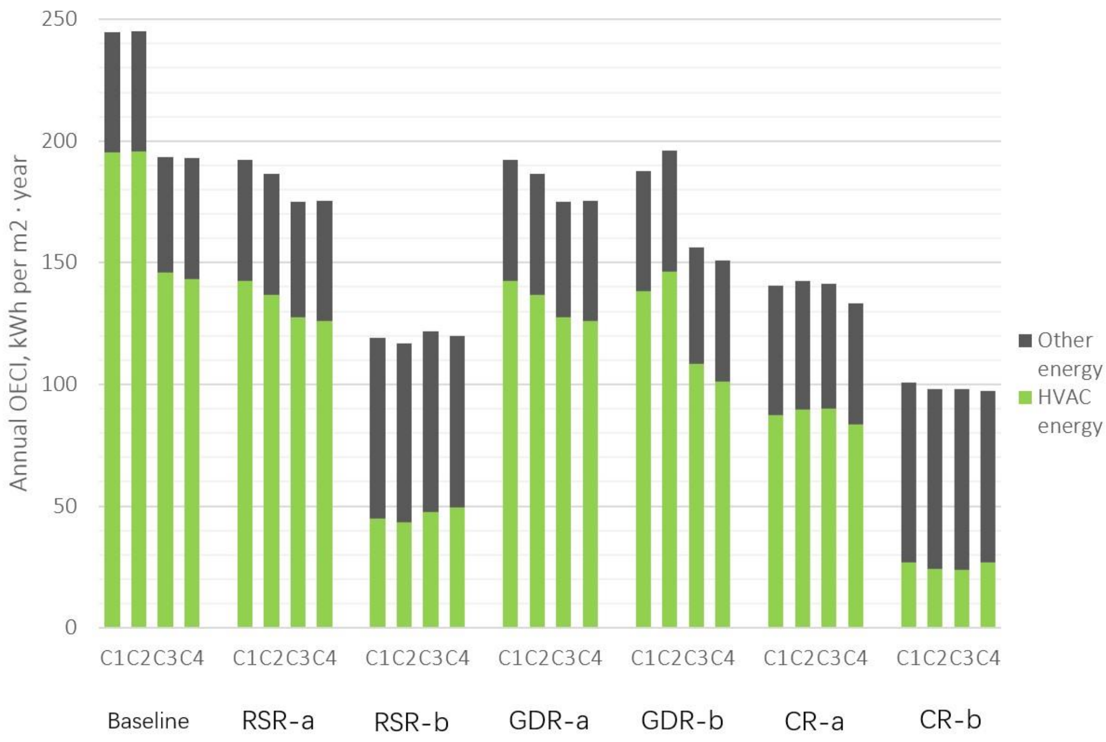

Figure 5.15: BEM results of annual OECI in different RURB scenarios and reference building types

Following the OECI data above, the energy conservation rate between retrofit scenarios and the baseline scenario can be obtained in Table 5.14:

Table 5.14: Energy conservation rate of HVAC and Total OECI compared to the Baseline scenario

Retrofit Scenarios		Cluster 1 (6F): Dilapidated Apartment	Cluster 2 (8F): Dilapidated Apartment	Cluster 3 (10F): Old apartment	Cluster 4 (30F): Old tower
RSR-a	HVAC	26.9%	30.0%	12.5%	12.1%
	Total	21.5%	24.0%	9.5%	9.0%
RSR-b	HVAC	76.9%	77.9%	73.8%	68.7%
	Total	51.3%	52.4%	41.9%	40.2%
GDR-a	HVAC	26.9%	30.0%	12.5%	12.1%
	Total	21.5%	24.0%	9.5%	9.0%
GDR-b	HVAC	29.1%	25.1%	25.6%	29.4%

	Total	23.3%	20.1%	19.3%	21.8%
CR-a	HVAC	55.3%	54.2%	38.3%	41.6%
	Total	25.2%	27.4%	9.4%	11.7%
CR-b	HVAC	89.1%	90.1%	87.7%	86.1%
	Total	58.8%	60.1%	49.4%	49.6%

Generally, it is found that the HVAC energy consumption can be dramatically reduced by applying energy efficient-retrofit techniques as in the RSR-b and CR scenarios. Yet the total OECI for the RSR-b and CR-a scenarios remain high while the 'other energy use' increases. From the design of the retrofit scenarios, the additional energy consumption is caused by introducing more qualitative improvements such as lifts and air purifiers. Furthermore, the limited energy conservation effect of the RSR-a scenario from 9.0% to 24.0% and the GDR-b scenario from 19.3% to 23.3% show that the isolation between system players will significantly hinder RURB effectiveness - even though the residents have enough budget while the government has a strong administrative ability to cover all construction works for retrofitting a building's external walls and roofs.

This confirms the conflict between energy conservation objectives and residents' demands for improved indoor environmental quality (discussed in Chapter Two). However, the OECI results showed that it is still possible for the advanced and more comfortable scenarios to achieve up to 58.8% energy conservation compared to the current conditions of old residences with no new equipment or lifts introduced, by applying scientific retrofit measures as in the CR-b scenario. This provides encouraging evidence for the retrofit scenario design based on the developed RURB system theory of system interactions.

It is also found that the OECI of HVAC equipment can achieve very high results in the RSR-b and CR-b retrofit scenarios. The selection of retrofit measures from the library showed a positive result for energy conservation by introducing a household radiator heating system to replace the conventional heating strategy of using split electronic ASHP conditioners. For the winter heating in the case study HSCW zone, a radiator heating system with high-efficiency natural gas boilers can easily achieve up to 94.2% reduced heating energy consumption (as 90.1% for total HVAC, in the CR-b scenario for clustered residence type 2) combined with the retrofit of a building's external façade. Furthermore, the hot-water radiator system provides thermal radiation rather than thermal convection from ASHP, which has been proven by many scholars to be a much more comfortable type of heat transfer.

5.6. Calculations of retrofit criteria

As the building energy simulation method can only provide operating energy consumption data, it is necessary to calculate the other quantitative energy consumption and cost data, based on the concepts of Life Cycle Assessment (LCA), to obtain the other retrofit criteria results. To avoid misleading energy data with different energy resources, normalization of energy values is applied to convert all site energy use in this research into standard source energy in kWh based on the GB/T 2589-2020 (State Administration for Market Regulation and Standardization administration, 2020) national standard for energy calculation.

5.6.1. Retrofit Investment Energy Consumption (RIECI)

Retrofit Investment Energy Consumption Intensity (RIECI) refers to $\overline{E_r}$ as the global one-off energy use during the retrofit construction for engineering, materials, transportation and replacement of equipment but excluding building operating energy use. The unit of RIECI is kWh per m^2. Based on the property being retrofitted, the energy consumption of onsite construction labour is not considered. The calculation of RIEC uses the following formula (2) based on LCA theory:

$$E_r = E_m + E_t + E_c \tag{2}$$

Where,

E_r ---- Total retrofit investment energy consumption

E_m ---- Energy consumption of retrofit material production

E_t ---- Energy consumption of retrofit material transportation

E_c ---- Energy consumption of construction, which is not considered in this retrofit study

Firstly, the energy consumption of retrofit materials is calculated based on the concept of the embodied energy of building materials calculated by Chen et al. (2022) and the quality of material used, following formula (3):

$$E_m = \sum_{j=1}^{k} (1 + \lambda_j)\, \mu_j \left(\sum_{i=1}^{n} q_{ij} e_{ij}\right) \tag{3}$$

Where,

k ---- Total variety number of retrofit materials, devices, and equipment

λ j ---- Loss coefficient of retrofit material j during production

μ j ---- Replacement coefficient of retrofit material j, μ j = 1 for retrofit calculation

qij ---- The quality of material j provided from location i

eij ---- The energy consumption to produce a unit mass of material j at location i, calculated as material embodied energy

In this case study, the embodied energy and loss efficiency data of used retrofit materials are summarised in Table 5.15:

Table 5.15: Embodied energy and loss efficiency of retrofit materials

Material	Embodied energy		Loss efficiency	
	kJ / kg	kWh/kg	production	transportation
◆ Cement	5500	1.528	0.025	0.025
◆ Sand	60	0.017	0.025	0.025
◆ Lime	5300	1.472	0.025	0.025
◆ Glass	16000	4.444	0	0
◆ Asphalt	3000	0.833	0.05	0.05
◆ Linoleum	77200	21.444	0.05	0.05
◆ Cement mortar (cement/sand/water = 1/3/0.65)	1222	0.339	0.05	0.05
◆ Lime mortar ◆ (lime/sand/water = 1/3/0.65)	1178	0.327	0.05	0.05
◆ Polystyrene Granule (granule/water = 1/2)	34650	9.625	0.05	0.05
◆ Polystyrene insulation board (EPS, XPS)	105000	29.167	0.05	0.05

Secondly, transportation energy consumption is calculated based on transport vehicle capacity, vehicle numbers, fuel consumption and the quality of each retrofit material, device and item of equipment (see Table 5.3). The vehicles used for transportation are the small delivery truck type with a 7-ton load, the diesel oil consumption rate is 0.18 litre per kilometre per truck for equipment and devices. For the large truck type with a 15-ton load, the diesel oil consumption rate is 0.25 litre per kilometre for materials, windows and lifts. Moreover, retrofit materials for walls, roofs and lifts should be calculated in per-building units with a total delivery journey of 30 km for a single trip (total of 60 km); however, each household should be individually calculated for the vehicle with a delivery length of 15 km (total of 30 km) per window, door, item of indoor equipment and device based on the nature of the residential building.

$$E_t = \sum_{j=1}^{k}(1+\lambda_j)\,\mu_j\,(\sum_{i=1}^{n} q_{ij}e_{tl}d_l) \quad (4)$$

Where,

k ---- Total variety number of retrofit materials, devices, and equipment

λ_j ---- Loss coefficient of retrofit material j during transportation

μ_j ---- Replacement coefficient of retrofit material j, $\mu_j = 1$ for retrofit calculation

q_{ij} ---- The quality of material j transported from location i

e_{tl} ---- The fuel energy intensity to transport a unit mass of material j with a unit distance, as 2.275 MJ $(kg\bullet km)^{-1}$ for truck

dl ---- Total transportation distance

For retrofit equipment and devices, using the integer vehicle number formula (5) with diesel oil consumption:

$$E_t = \sum_{j=1}^{k}(1+\lambda_j)\,\mu_j\,(\sum_{i=1}^{n} w_{ij}v_o c_o d_l) \quad (5)$$

Where,

w_{ij} ---- The integer vehicle number to transport material j from location i

v_o ---- The diesel oil consumption to transport a unit mass of material j with a unit distance, as 0.18 L/km for a 15-ton truck

c_o ---- The low-calorific value of diesel oil, as 35659 kJ/L

Thirdly, the RIECI index is hence calculated as the sum of E_r divided by the total indoor residential area. Additionally, the lifespan of retrofit measures is assumed as 30 years based on LCA considering the update frequency of new building energy efficiency standards. Furthermore, the conversion coefficient between primary site energy to secondary source energy is 3.167 for electricity, 1.084 for natural gas (for heating), and 1.050 for diesel oil (for transportation energy).

In summary, the calculated RIECI are shown in Table 5.16 and Figure 5.16:

Table 5.16: RIECI calculation results. Unit: kWh / m^2

Retrofit scenario	Cluster 1 (6F): Dilapidated Apartment	Cluster 2 (8F): Dilapidated Apartment	Cluster 3 (10F): Old apartment	Cluster 4 (30F): Old tower
RSR-a	21.9	20.9	21.2	29.4
RSR-b	25.6	23.5	24.2	32.1
GDR-a	21.9	20.9	21.2	29.4
GDR-b	104.8	92.9	82.2	66.6
CR-a	127.8	114.2	97.7	96.7
CR-b	76.8	68.2	55.4	58.2

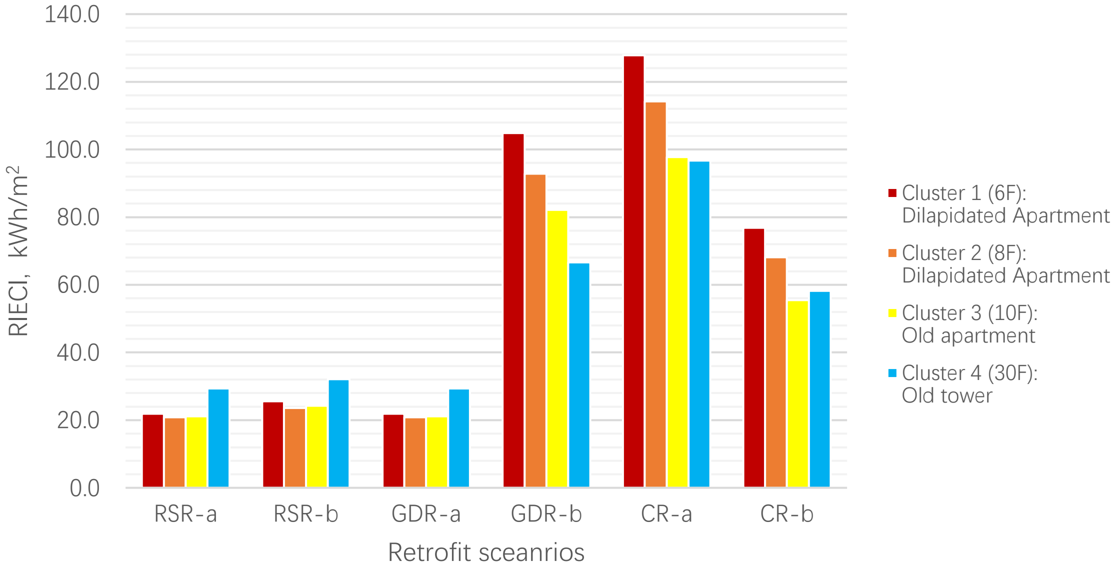

Figure 5.16: Calculated results of RIECI in different RURB scenarios and reference building types

5.6.2. Retrofit Investment Cost Intensity (RICI)

Similar to RIECI, Retrofit Investment Cost Intensity (RICI) refers to the global one-off economic cost $\overline{C_r}$ (as a required payment) during the retrofit construction for engineering, material, transportation and replacement of equipment but excluding building operating costs. The unit of RICI for this RURB case study is CNY per m^2. Particularly, the costs of onsite construction labour should also be included compared with RIECI, which contains the transportation, tools and salary expenses of the workers involved. The calculation of RICI uses the following formula (6) based on LCA theory:

$$C_r = C_m + C_t + C_l \quad (6)$$

Where,

Cr ---- Retrofit investment cost (RIC)

Cm ---- Cost of retrofit material, devices, and equipment

Ct ---- Cost of material transportation

Cl ---- Cost of the construction labour force.

The unit price and loss coefficient collected in the case study area for construction materials and HVAC equipment are listed in Table 5.17:

Table 5.17: RICI of retrofit materials, labour, and equipment (currency: Chinese Yuan)

Retrofit aspect	**Retrofit material (thickness) & equipment**	**Unit price**	**Unit**	**Loss coefficient**
External wall & roof	◆ Cement mortar 20mm	3.6	m^2	0.05
	◆ Crack-resistant mortar 20mm	3.6	m^2	0.05
	◆ APG - Adhesive polystyrene granule mortar 50mm	70	m^2	0.05
	◆ Lime mortar 20mm	4	m^2	0.05
	◆ EPS - expanded polystyrene board 40mm	100	m^2	0.05
	◆ XPS - extruded polystyrene board 40mm	200	m^2	0.05
	◆ SBS - asphalt waterproof rolls 5mm	30	m^2	0.05
Labour	◆ Removal (external wall and roof)	10	m^2	/
	◆ Installation (external wall and roof)	20	m^2	/
	◆ Work at height (external wall)	20	m^2	/
	◆ Work at height (external window)	30	m^2	/
External window	◆ Low-E double-layer insulating glass 6+12+6, air layer, aluminium alloy window frame	500	m^2	0
	◆ Low-E double-layer insulating glass 6+12+6, argon gas layer, PVC window frame, double silver plating	800	m^2	0
External door	◆ Galvanised steel anti-theft door (expanded perlite insulation layer)	1000	per	0
HVAC	◆ Split air conditioner (EER/COP*:3.2/2.6)	2300	per	0
	◆ Split air conditioner (EER/COP:3.6/3.0)	4300	per	0
	◆ Radiator heating system (family unit with boiler 99% efficiency, natural gas)	11000	per household	0
	◆ Air Purifier	2000	per bedroom	0
Shading	◆ Venetian blind	100	per window	0
Public lighting	◆ LED lighting system for public corridor	1000	per floor	0
Lift	◆ External lift (15 kW), tube well, and earthwork	500000	per lift	0
Fire safety	◆ Indoor smoke detector (battery)	150	per room	0

*Note: EER: energy efficiency Ratio, for cooling mode. COP: coefficient of performance, for heating mode.

According to the above price conditions for retrofit measures, the calculated RICI results for different scenarios are shown in Table 5.18 and Figure 5.17:

Table 5.18: RICI calculation results. Unit: Chinese Yuan / m^2

Retrofit scenarios		Cluster 1 (6F): Dilapidated Apartment	Cluster 2 (8F): Dilapidated Apartment	Cluster 3 (10F): Old apartment	Cluster 4 (30F): Old tower
RSR-a	Resident pays	166.0	163.0	166.0	194.0
	Government pays	/	/	/	/
	Transportation	3.5	3.4	3.9	3.5
	Total	169.5	166.4	169.9	197.5
RSR-b	Resident pays	753.0	585.0	611.0	534.0
	Government pays	/	/	/	/
	Transportation	6.6	5.6	6.4	5.7
	Total	759.6	590.6	617.4	539.7
GDR-a	Resident pays	124.0	121.0	123.0	152.0
	Government pays	43.0	43.0	43.0	43.0
	Transportation	3.5	3.4	3.9	3.5
	Total	170.5	167.4	169.9	198.5
GDR-b	Resident pays	0.0	0.0	0.0	0.0
	Government pays	131.0	113.0	96.0	95.0
	Transportation	0.7	0.6	0.4	0.4
	Total	131.7	113.6	96.4	95.4
CR-a	Resident pays	330.0	198.0	141.0	163.0
	Government pays	210.0	180.0	166.0	139.0
	Transportation	5.1	4.3	5.1	4.4
	Total	545.1	382.3	312.1	306.4
CR-b	Resident pays	659.0	523.0	545.0	492.0
	Government pays	303.0	245.0	227.0	182.0
	Transportation	7.3	6.1	6.8	6.1
	Total	969.3	774.1	778.8	680.1

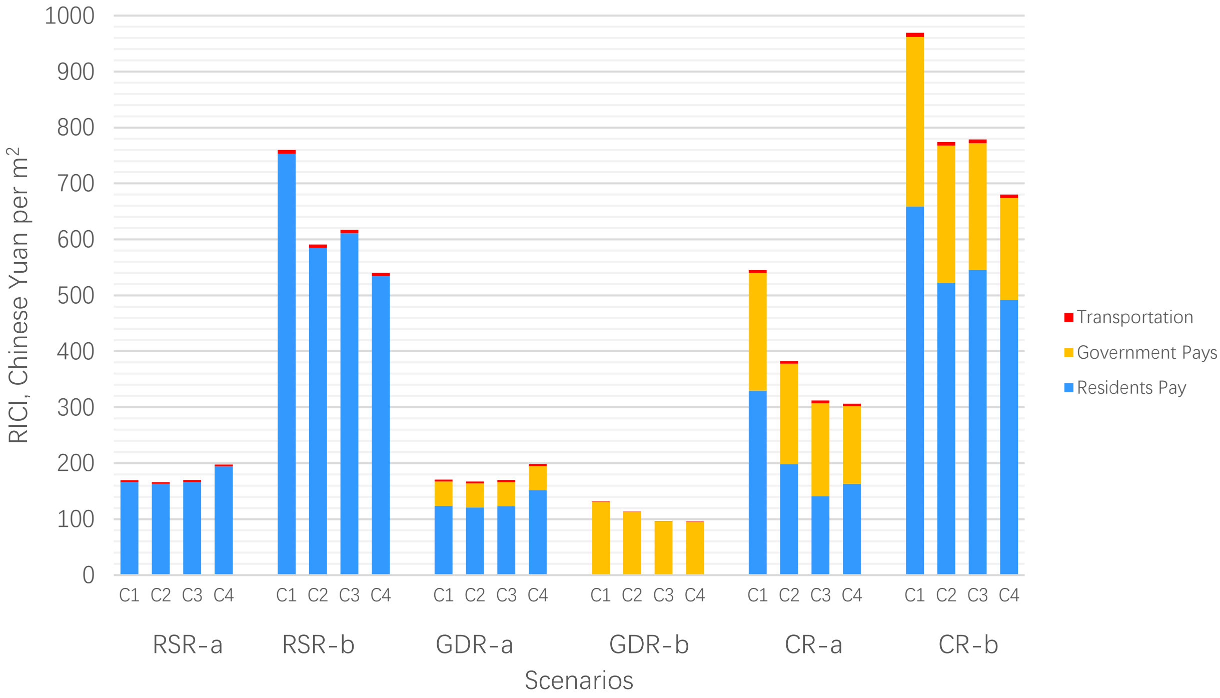

Figure 5.17: Calculated results for RIECI in different RURB scenarios and reference building types

The RICI data above indicate the proportion of the economic cost of RURB paid by residents and the government based on the designed retrofit scenarios. The features of the RICI data followed the global degree limits of each scenario set based on the RURB system theory and social survey results. To residents, the overall RICI is designed to be within the affordable price - since even the most expensive CR-b scenario for the most unfavourable condition (cluster 1 building type) is ¥969.3 per m^2. However, this still lies within the maximum budget allowance of ¥1,000 per m^2 (¥100,000 for the 100 m^2 household plan and ¥60,000 for the 60 m^2 household plan, from the questionnaire). For RURB policymakers, the average prices of three types of governmental support are clarified, including the subsidy demand for HVAC equipment only (yellow data in Figure 5.17, above, for the GDR-a scenario), for retrofitting all building external walls and roofs to meet the newest BEES requirement (the GDR-B scenario, above) and with an additional subsidy for both a lift and the cost of advanced retrofit techniques with better thermal performance (yellow data in CR-b scenario above).

More specifically, the transportation cost C_t can be seen to be very moderate amounting to a very small proportion of the total RICI, which is a one-off payment when considering RURB in LCA thinking with a 30-year effect. The GDR-b scenario has the least amount because all the materials for the building façade retrofit will be delivered simultaneously.

5.6.3. Retrofit Time Cost (RTC)

Since the retrofit construction works may unavoidably cause access difficulties, pollution and noise problems, the Retrofit Time Cost (RTC) is another important factor to influence the decision-making for RURB designs. It is the global limit collected from the questionnaire survey as a maximum acceptable time in the case study area. By reviewing the RURB projects report literature, the average time used for each retrofit measure can be summarised in Table 5.19:

Table 5.19: Individual time cost and number of labourers required for the retrofit measures

Retrofit measures	Retrofit work type	Time cost (days)	Labour demand (people)
◆ External window	Replacement	1	3
◆ Heating and cooling devices – air conditioner	Replacement	1	2
◆ Radiator heating system	New	3	3
◆ External door	Replacement	1	2
◆ Shading	New	1	1
◆ Air purifier	New	1	0
◆ Lift	New	40	5
◆ External wall – APGC, EPS, XPS – apartment	Retrofit	45	8
◆ External wall – XPS – tower	Retrofit	60	10
◆ Roof - XPS	Retrofit	30	5
◆ Public space lighting	Repair	3	3
◆ Indoor smoke detector	New	1	1

The maximum RTC for each retrofit scenario can be calculated based on the clustered building types. It is also the most unfavourable condition – the households may take a whole day to replace only one type of HVAC equipment. Since the questionnaire survey asked for the allowance of time cost, the RTC shows a very clear allowance range of time cost due to the retrofit construction work: no more than 60 days. Therefore, the selected packages of retrofit measures are verified as being below the maximum RTC limit.

Table 5.20: RTC calculation results. Unit: day(s)

Retrofit scenarios	Cluster 1 (6F): Dilapidated Apartment	Cluster 2 (8F): Dilapidated Apartment	Cluster 3 (10F): Old apartment	Cluster 4 (30F): Old tower
RSR-a	2	2	2	2
RSR-b	40	40	40	9
GDR-a	2	2	2	2
GDR-b	45	45	45	60
CR-a	45	45	45	60
CR-b	45	45	45	60

Figure 5.18: Calculated results for RTC in different RURB scenarios and reference building types

Table 5.20 and Figure 5.18 show that the outdoor lift installation and retrofitting of the building's external walls are the most time-consuming retrofit measures. The lift installation works require at least 40 days excluding the production time cost of the lift machines. The retrofitting of external walls in apartment residences may take at least 45 days and even longer than 60 days for tower residences because of the difficulty of working-at-height.

5.6.4. Annual Operating Cost Intensity (OCI)

Annual Operating Cost Intensity (OCI) is an annual density index related to the operating energy and additional maintenance cost caused by all retrofit measures, such as lift energy and maintenance costs and air purifiers, in a unit of currency per $m^2 \cdot$ year. In this study, OCI as $\overline{C_o}$ is calculated based on the OECI data (generated from the building simulation in section 6.2.3) and multiple local prices for electricity and natural gas for residential use. The prices of electricity and natural gas are obtained from the governmental price list for the Chongqing urban area: ￥0.52 per kWh for electricity and ￥2.039 per m^3 (as ￥0.206 per kWh) based on the natural gas energy coefficient of 35,588 KJ/m^3 (State Administration for Market Regulation and Standardization administration, 2020)).

Considering the quantitative retrofit benefits from energy efficiency and qualitative benefits from comfort, accessibility and safety improvements, the OCI is accordingly divided into two types for OECI: the operating cost of HVAC equipment and the total operating cost. The calculated results are shown in Table 5.21 and Figure 5.19:

Table 5.21: Annual OCI calculation results. Unit: Chinese Yuan per $m^2 \cdot$ year

Retrofit scenarios		Cluster 1 (6F): Dilapidated Apartment	Cluster 2 (8F): Dilapidated Apartment	Cluster 3 (10F): Old apartment	Cluster 4 (30F): Old tower
Baseline	HVAC	32.1	32.1	24.0	23.5
	Total	40.2	40.3	31.8	31.7
RSR-a	HVAC	23.4	22.5	21.0	20.7
	Total	31.6	30.6	28.8	28.8
RSR-b	HVAC	7.9	7.6	6.7	7.7
	Total	20.0	19.6	18.8	19.3
GDR-a	HVAC	23.4	22.5	21.0	20.7
	Total	31.6	30.6	28.8	28.8
GDR-b	HVAC	22.7	24.1	17.8	16.6
	Total	30.8	32.2	25.6	24.8
CR-a	HVAC	14.3	14.7	14.8	13.7
	Total	23.1	23.4	23.2	21.9
CR-b	HVAC	4.7	4.2	4.1	4.5
	Total	16.8	16.2	16.2	16.1

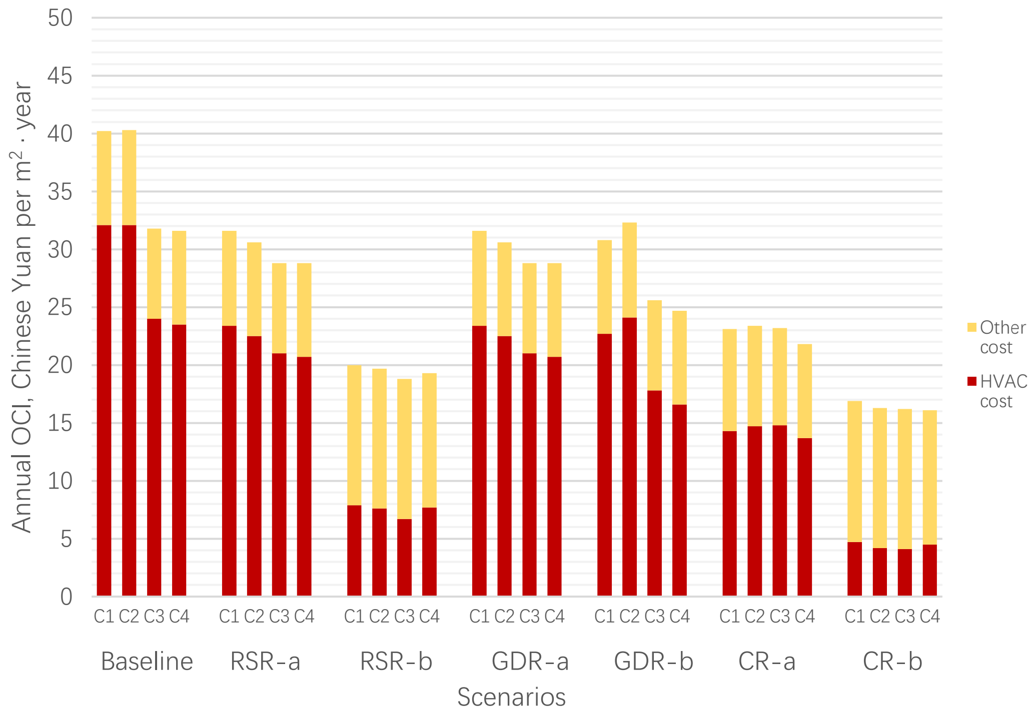

Figure 5.19: Results for annual OCI in different RURB scenarios and reference building types

Following the OCI data above, the economic cost-saving rate between retrofit scenarios and baseline scenarios can be obtained in Table 5.22:

Table 5.22: Cost saving rate of HVAC and Total OECI compared with the Baseline scenario

Retrofit Scenarios		Cluster 1 (6F): Dilapidated Apartment	Cluster 2 (8F): Dilapidated Apartment	Cluster 3 (10F): Old apartment	Cluster 4 (30F): Old tower
RSR-a	HVAC	26.9%	30.0%	12.6%	12.2%
	Total	21.4%	24.1%	9.4%	9.0%
RSR-b	HVAC	75.5%	76.5%	72.2%	67.2%
	Total	50.2%	51.4%	40.9%	39.1%
GDR-a	HVAC	26.9%	30.0%	12.6%	12.2%
	Total	21.4%	24.1%	9.4%	9.0%
GDR-b	HVAC	29.2%	25.1%	25.6%	29.4%
	Total	23.4%	20.1%	19.5%	21.8%
CR-a	HVAC	55.3%	54.2%	38.3%	41.6%
	Total	25.0%	27.3%	9.4%	11.6%
CR-b	HVAC	88.4%	89.7%	87.2%	85.8%
	Total	58.2%	59.8%	49.1%	49.3%

On average, the saving rate of OCI is less compared with the OECI, with up to 88.4% reduction rate for HVAC OCI and 59.8% for total OCI. It can be inferred that the continuously operating mode of additional lift and air purifiers as additional operating costs have caused this result with a higher EUI for electricity. More importantly, the total OCI saving rate for RSR scenarios from 9.0% to 51.4% shows the minimum and maximum value of retrofit measures taken by residents only, without any help from RURB policymakers. Meanwhile, the total OCI saving rate for the GDR-b scenario from 21.8% to 23.4% shows the effectiveness of government-driven retrofits for a building's external walls and roofs. Since RURB residents do not need to pay anything in the GDR-b scenario, this shows that the strength of the government itself can provide up to ¥9.4 per m^2 energy bill reduction each year, for an annual saving of 564 CNY for $60m^2$ households and 940 CNY for $100m^2$ households.

Similar to the OECI result, Table 5.22 shows that the OCI of HVAC equipment can save significantly on the total cost in retrofit scenarios RSR-b and CR-b due to the change of heating equipment type from electrical AHSP to natural gas radiators. In these two scenarios, the HVAC operating cost has fallen by over 50% compared to the other costs. Based on the low local price of natural gas, the radiator system has proved its ability to provide energy saving, operating cost saving and a more comfortable radiant heat supply, as a win-win retrofit technique for the case study. It has also evidenced the importance of local advantages for the design of RURB scenarios, as it was discussed as one of the RIODF provided by scholars as RURB system players.

5.7. Multi-criteria Decision Making (MCDM) analysis

RURB involves a vast number of complex quantitative and qualitative variables. Hence an assessment approach that considers many variables and impact factors simultaneously should be applied to analyse and optimise the different scenario results. Retrofit benefits and costs can refer to individual criteria such as energy saving, time, investment and comfort. Since the conventional result analysis methods may not be sufficient for qualitative retrofit results in RURB research, multi-criteria decision-making methods are found to be extremely useful in developing modern sustainability and energy conservation in buildings.

In this section, the BEM and calculation results of the retrofitted scenarios are analysed in respect of energy saving, time cost, economic cost, comfort improvements, accessibility improvements and safety improvements. They are considered as different retrofit criteria to describe the variety of retrofit benefits and costs. In this case, the multicriteria assessment method is adapted to help RURB system players make decisions and provide evidence for future policymaking and the selection of RURB techniques.

5.7.1. Review of MCDM Methods

Initially, several popular methods of MCDM are reviewed. Their advantages and limitations are discussed to identify an appropriate method for this RURB study.

1) Analytic Hierarchy Process (AHP)

   In Saaty's theory (Saaty, 1988), the analytic hierarchy process (AHP) is by definition a full aggregation method that structures problems according to a minimum of three hierarchy levels where the top element is the goal of a decision, the second is the criteria and the lowest level comprises the alternatives (Ishizaka and Nemery, 2013, Saaty, 1988). The AHP method is useful for MCDM cases whose criteria have significant hierarchic relationships, while the criteria, local alternatives and global alternative priorities should be calculated for ranking using a comparison matrix. For this RURB study, as reviewed, designed, and discussed so far, the criteria for the retrofitting results may include energy, environmental, economic, and social aspects which, without a very clear hierarchic relationship, may still cause conflicts between each other. Therefore, the AHP method may not be very efficient for this study.

2) Analytic Network Process (ANP)

   Similar to the AHP method, Saaty's analytic network process (ANP) is an advanced MCDM approach that deals with dependencies, unlike AHP which is better for MCDM with independent criteria (Saaty, 2013). ANP can provide more realistic and accurate results while the criteria are correlated and it can model feedback loops using clusters with inner dependency to replace the liners in the AHP method (Saaty, 2005). For this RURB research, ANP might be a possible method if all dependent criteria clusters and alternative clusters are fully defined and formulated (Ishizaka and Nemery, 2013). As the criteria of this study will be applied to multiple classified building types, the influence matrices could be complicated but trustworthy. This leaves a concern about the effectiveness issue given the ANP method could be time-consuming for this RURB study with its complex scenarios, different building types and complicated dependent criteria.

3) Multi-attribute Utility Theory (MAUT)

If the decision maker wants to optimise a function that aggregates and represents all their preferences, multi-attribute utility theory (MAUT) can be considered a suitable MCDM method. The utility function is a way of measuring the desirability or preference of alternatives, just like the comfort improvement for this study. It has been widely stated that when the decision maker can construct this “utility function”, the use of MAUT is recommended rather than the AHP method (Ishizaka and Nemery, 2013). The utility score could be seen as the degree of well-being that alternatives provide to decision makers, hence, if the overall aim of retrofitting is the energy-saving and environmental improvement to RURB policymakers only, then MAUT should be the suitable method. However, in this RURB study, each criterion is correlated with four different system players, which means four decision-makers would have their unique marginal utility values and corresponding global utility for the alternatives, so the aggregation modelling should be multiplied four times for each alternative. Hence, for this study, the MAUT method implies overcomplicated marginal utilities and aggregations of global utility.

4) Preference Ranking Organization Method for Enriched Evaluation (PROMETHEE)

Developed by Brans (1982), the PROMETHEE, also called Prometheus and Gaia, the method is one of the MCDM methods which provide decision-makers with a ranking of actions based on degrees of preference. This is an outranking approach that has great ability in making the selection of one alternative from a series of different alternatives for further evaluation, especially where there are multiple decision criteria involved (Brans and Mareschal, 2005). As this RURB research is quite similar to many alternative retrofitting scenarios, this approach might be more appropriate to help policymakers and residents find a compromise and optimal scenario among many choices. However, the PROMETHEE method uses repeated evaluation logic for different criteria, which may lead to contradictions arising during the weighting process.

Therefore, the Analytic Network Process (ANP) and the Preference Ranking Organization Method for Enriched Evaluation (PROMETHEE) methods are argued to be the appropriate MCDM theories to suit the retrofit criteria conditions in this study. Later, the review of the current literature uses MCDM as a core analysis tool to select the most reasonable of these two MCDM methods.

5.7.2. Current MCDM practices in building retrofitting

Because of the complex nature of building retrofitting variables, many retrofitting studies have considered MCDM for the analysis of their results. A series of relevant published papers have been selected and reviewed to identify an appropriate MCDM method for this RURB research. The MCDM methods from Triantaphyllou (2000) and Stein (2013) for example, show that RURB is similarly seeking an assessment system with each element ranked and emphasised based on reliable retrofit effects data. Furthermore, Moghadam and Lombardi (2019a) produced an extremely comprehensive, multi-criteria, spatial, decision support system for energy retrofitting of the building stock. They developed a new, interdisciplinary and coherent interactive MCDM method based on urban energy planning and a GIS database; they have also created quantified links between energy, environmental, technical, economic and social performances of retrofitting interventions.

More relevant studies from Chen *et al.* (2019) and Asadi *et al.* (2012) provide insights into assessing residential building retrofit using the outranking approach. Chen *et al.* studied a Norwegian case by selecting energy efficiency measures and defining them into three types of variables: passive, active and renewable. These variables have been combined into a total of 18 retrofit combination packages and grouped into four retrofit scenarios, as “three levels of moderate retrofit” and one “extensive retrofit” based on the potential for energy conservation. Two levels of assessments are computed using the MCDM method: the first one combines energy, economic and environmental assessments whilst the second one is an adapted model with social values from various stakeholders’ perspectives.

Accordingly, this type of study can present a comprehensive overview of the physical variable combinations packages for energy, economic and environmental saving potentials and it can assess and quantify stakeholders’ perspectives on the proposed combination packages by using outranking methods as a matrix of weighting factors.

The above research has proven the theory's ability to enable wider engagement from residents in RURB decision-making. However, the MCDM theory in this study is not comprehensively introduced, also the study by Chen *et al.* is a single-building scale simulation so the matrix weighting could become too complicated if the scenarios are multiplied by different building types, in which case, Saaty's ANP theory (Saaty, 2005) could be more suitable to create a network layer of scenarios and building types to generate the weighted supermatrix for the synthesised priorities among a large number of possible scenario alternatives.

Successful practices reviewed by Xu *et al.* (2015) achieved the best selection of sustainable building energy efficiency retrofits for hotel buildings and Liu et al. (2018a) combined the ANP approach with other management methods to make decisions on building strategies. Similarly, Pakand and Toufigh (2017) used the ANP method to evaluate rammed earth samples from low-carbon buildings. Moazzen *et al.* (2020) modelled and found the most appropriate and affordable designs for school building retrofitting. They all showed the strength of the ANP method and its ability to discover the best choice from options with unique criteria in a network relationship.

Referring to large-scale retrofit research, Dirutigliano *et al.* (2018) used the PROMETHEE method to assess district-scale data. They found the best strategies for energy retrofit alternatives in their case study to be optimal for both economic and socio-environmental benefits for the local community. They defined three quantitative criteria: investment cost, energy bill savings and the cost of maintenance and replacement. They also considered reliability, the improvement of internal thermal comfort, and social image and awareness as three qualitative criteria during their MCDM. Although the alternative in this study was five retrofitting measures rather than different retrofitting scenarios, it successfully outranks the retrofit alternatives, which means it has proven the feasibility and effects of the PROMETHEE MCDM method of assessing retrofit results on a large scale and with many competitive criteria.

5.7.3. Design of the Analytic Network Process (ANP)

Based on its developed theory to analyse multiple criteria with complex interactions, Analytic Network Process (ANP) is reviewed and selected as an appropriate method for this research into RURB decision-making, with the software engine *Super Decisions* applied during the calculation steps. Based on the ANP theory (Saaty, 2013, Saaty, 2005) and with the retrofit system boundary clarified, the ANP network structure of RURB system criteria was obtained as in Table 5.23 and Figure 5.20:

Table 5.23: Defined RURB criteria

Criteria (as clusters in ANP)	Sub-criteria (as nodes in ANP)	Factor property
Energy (E)	Investment energy (E1)	Quantitative
	Operating energy (E2)	Quantitative
Cost (C)	Investment cost (C1)	Quantitative
	Time cost (C2)	Quantitative
	Operating cost (C3)	Quantitative
Comfort (T)	Indoor air quality (T)	Qualitative
Accessibility (A)	Lift installation (F)	Qualitative
Safety (S)	Public space lighting (S1)	Qualitative
	Indoor smoke detection (S2)	Qualitative

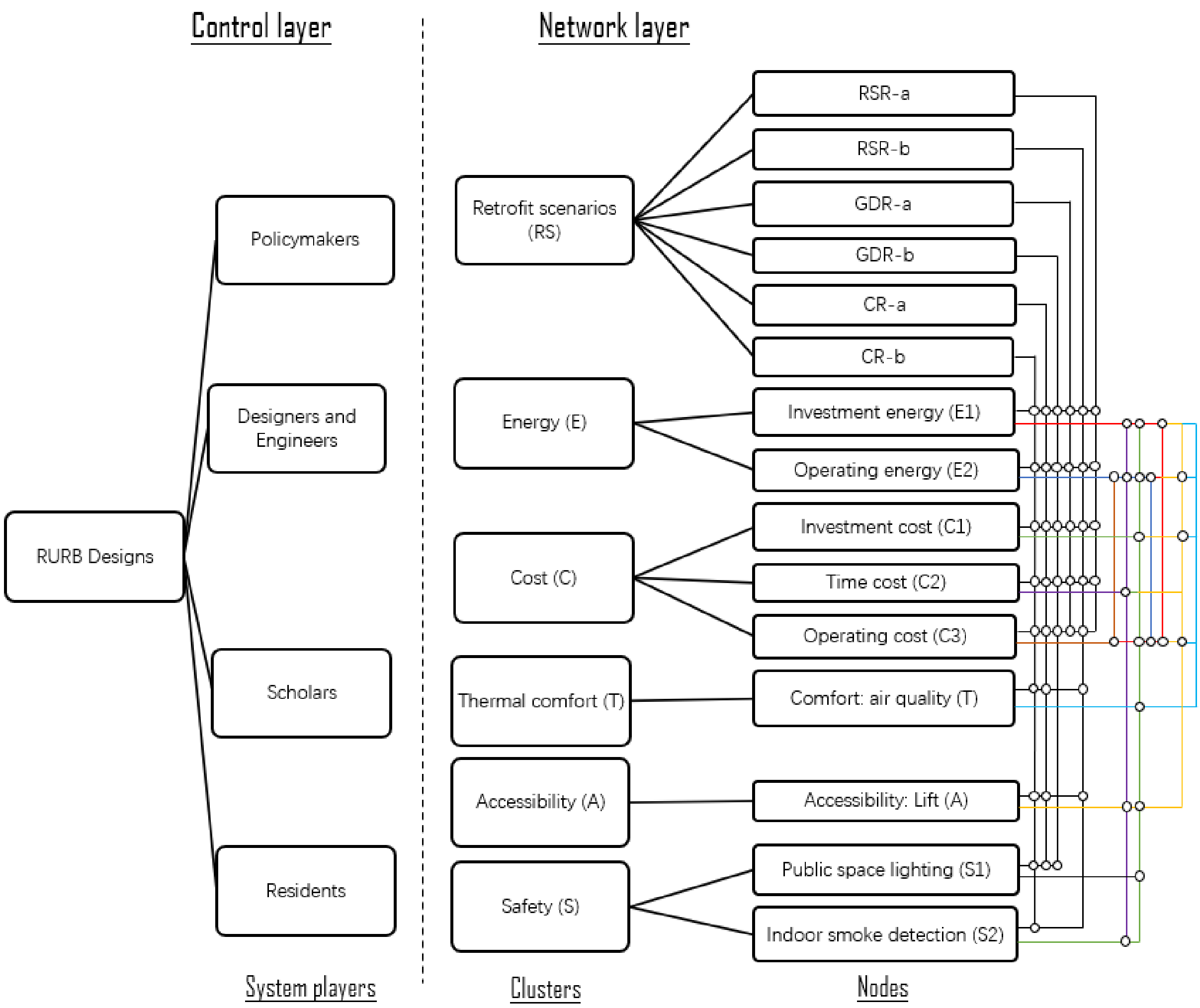

Figure 5.20: The structure of the ANP method for the RURB system

Secondly, following Saaty's ANP theory (Saaty, 2013), the judgement matrix is structured by using the pair comparison method to compare the RURB criteria as the supermatrix. To determine the weight value of each criterion, the Delphi method is used to collect the pair comparison opinion scores from 10 invited experts who have professional knowledge of RURB policymaking, designing and engineering, for a total of two rounds of questionnaire survey. Experts were asked questions about the importance level between the two criteria and scored on a scale of 1-9 to represent the importance value $A_{ij}$from equal importance to extreme importance or not important at all, as shown in Table 5.24:

Table 5.24: Pair comparison value method between criterion factors

Criterion	Factors		Importance of pair comparison	Value
A	i	j	Factor i and j are equally important	1
			Factor i is a little more important than j	3
			Factor i is more important than j	5
			Factor i is strongly more important than j	7
			Factor i is extremely more important than j	9
			The intermediate values of two adjacent judgments	2,4,6,8
			Factor i is a little ~ extremely less important than j	-1 ~ -9

Thirdly, the components of the ANP network layer can be assumed as C_1, C_2, C_3, ..., C_n, wherein C_j is composed by c_{ij} (*k=1, 2, ..., n*) with comparison analysis of C_i according to the impacts on c_{ij}. Later, sorting vectors of criteria W_{ij} can be acquired following the eigenvalue method based on the Delphi results, which are collected from experts and tested for their consistency coefficient. They can be written as a matrix form of local weight vector matrices.

$$W_{ij} = \begin{bmatrix} \omega_{i1}^{j1} & \omega_{i1}^{j2} & \cdots & \omega_{i1}^{jn} \\ \omega_{i2}^{j1} & \omega_{i2}^{j2} & \cdots & \omega_{i2}^{jn} \\ \vdots & \vdots & \vdots & \vdots \\ \omega_{in}^{j1} & \omega_{in}^{j2} & \cdots & \omega_{in}^{jn} \end{bmatrix} \tag{7}$$

Accordingly, the weightless supermatrix W_0 (or named as unweighted supermatrix) can be acquired which is composed of the sorting vectors affected by factors (sub-criteria) on the network layer of the ANP structure. Then, each factor matrix should be normalised to the column sum is 1, which means that it is necessary to weigh the factors of W_0 to get the normalised weighted supermatrix $\overline{W}$.

$$W_0 = \begin{bmatrix} \omega_{i1}^{j1} & \omega_{i1}^{j2} & \cdots & \omega_{i1}^{jn} \\ \omega_{i2}^{j1} & \omega_{i2}^{j2} & \cdots & \omega_{i2}^{jn} \\ \vdots & \vdots & \vdots & \vdots \\ \omega_{in}^{j1} & \omega_{in}^{j2} & \cdots & \omega_{in}^{jn} \end{bmatrix} \tag{8}$$

To obtain the sorted vector of the supermatrix, the comparisons of the importance of criteria C_i and C_j are introduced as H_j = [h_{1j}, h_{2j}, ..., h_{nj}] to obtain the weighted supermatrix $\overline{W}$, which is calculated as H multiplying W_0. Finally, to represent the relevance between weighted factors, it is necessary to apply the stability treatment to the weighted supermatrix by calculating the limit relative rank vector as the limit supermatrix W_∞.

$$W_\infty = \lim_{k\to\infty} \left(\frac{1}{N}\right) \sum_{k=1}^{N} \overline{W}^k \tag{9}$$

Therefore, the synthesised weight value of each retrofit scenario designed can be obtained for the evaluation of RURB decision-making based on the limit supermatrix calculated by *Super Decisions* software.

5.7.4. Steps and Result

1) Creating an ANP model with clusters and nodes

Fundamentally, the ANP structure is developed based on the defined RURB criteria (as retrofit benefits and costs) in Table 5.23. In the Super Decisions interface, the retrofit scenarios are named as 'alternatives' to match their property for the final decision-making results, while the other clusters are created as clusters, and sub-criteria as nodes. Later, the connections between clusters and nodes are individually linked following their interactions with the network layer. The consequent visual ANP structure is presented in Figure 5.21:

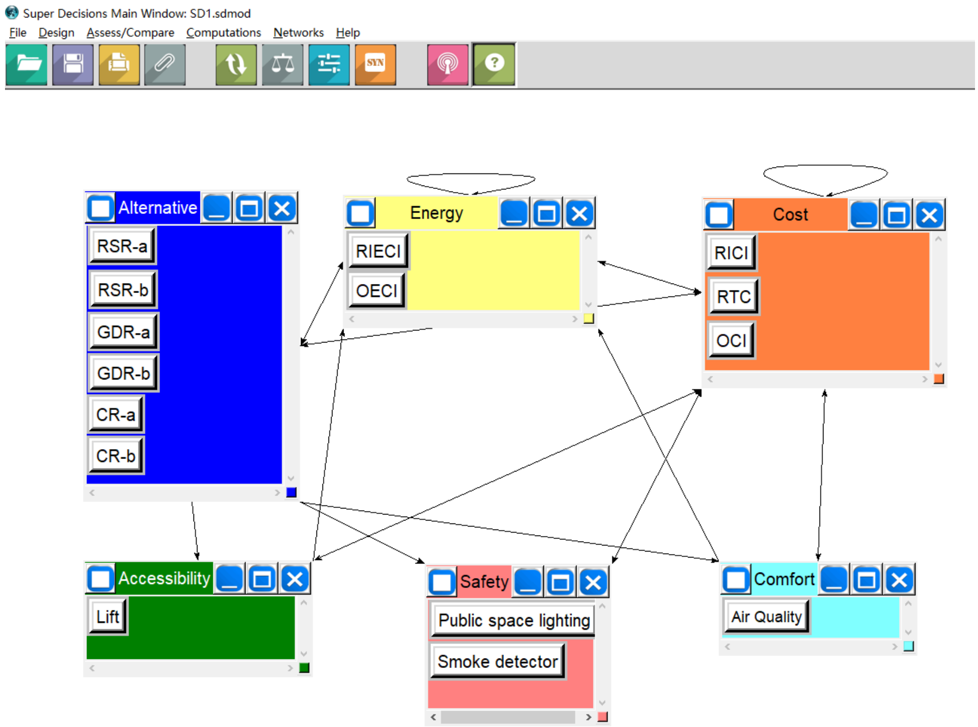

Figure 5.21: The ANP model of retrofit criteria introduced into the Super Decisions software

2) Determining pairwise comparisons between relative clusters and nodes

Following the clarified retrofit criteria in Table 5.23, the pairwise comparisons proceeded based on the Delphi method with 10 invited professionals. A total of 19 pairwise comparison figures (as established matrices from the above step) were provided to the professionals. They were asked to score the comparative importance between two sub-criteria (as nodes) based on one specific retrofit criterion (as a cluster) followed by the 1 to 9 scaling as mentioned in Table 5.24.

According to the principle of the Delphi method, once the first-round pairwise comparison results had been collected, the results from the professionals' questionnaire should be tested by the consistency ratio (CR), as the inconsistency value in Super Decisions. Both the highest and the lowest scores are removed to calculate the average value of the scored result. Afterwards, only the results with inconsistency values smaller than 0.1 were imported into the software for comparison by executing the commands "Assess/Compare" and then "Pairwise comparison", as shown in Figure 5.22.

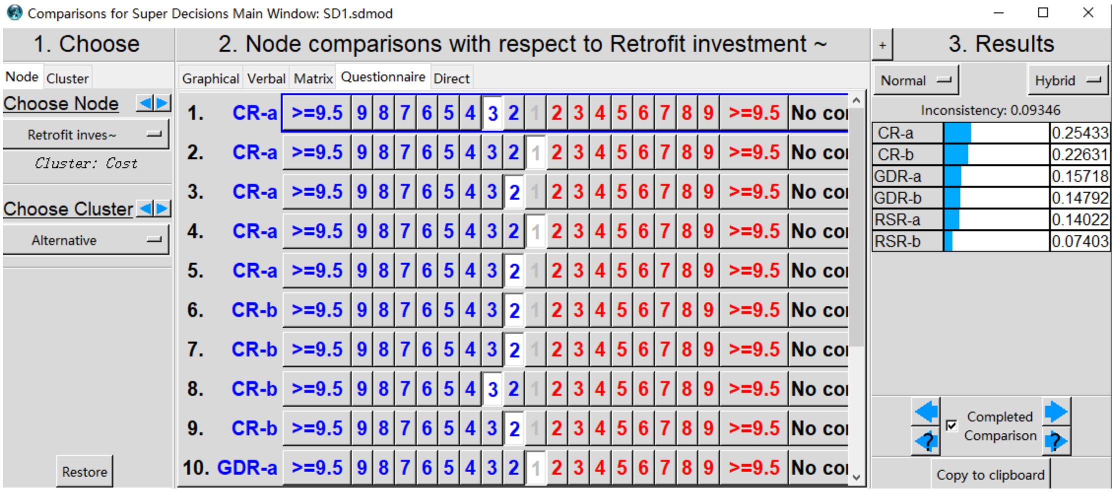

Figure 5.22: Importing the pairwise comparison results into the Super Decisions software

For the scored matrix that does not meet the requirement of the consistency test, the second round of professional questionnaires with the anonymous total votes of the first-round survey was then sent to the same professionals. In the second-round survey, they were asked if they wished to adjust their votes based on the opinions of other experts until all the pairwise comparison matrices have achieved the CR < 0.1.

3) Calculating the ANP super matrixes

Once the process of pairwise comparison had been completed, the calculation of three super matrices proceeded using the Super Decisions software for the following steps:

a) Executing the command “Do Computations” and then “Unweighted Super Matrix” to obtain the weightless supermatrix W_0.

b) Executing the command “Do Computations” and then “Weighted Super Matrix” to obtain the weighted supermatrix $\overline{W}$.

c) Executing the command “Do Computations” and then “Limit Super Matrix” to obtain the limit supermatrix W_∞.

Consequently, the calculated supermatrices are shown below in Tables 5.25 to 5.27:

Table 5.25: Unweighted (weightless) supermatrix

Cluster	Nodes	Retrofit Scenario						Energy		Cost			Comfort	Access	Safety	
		RSR-a	RSR-b	GDR-a	GDR-b	CR-a	CR-b	RIECI (E1)	OECI (E2)	RICI (C1)	RTC (C2)	OCI (C3)	(T)	Lift (A)	Light (S1)	Smoke (S2)
RS	RSR-a	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.12485	0.11180	0.14022	0.13341	0.13017	0.00000	0.00000	0.00000	0.00000
	RSR-b	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.11740	0.11225	0.07403	0.11802	0.14825	0.00000	0.00000	0.00000	0.00000
	GDR-a	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.15593	0.13816	0.15718	0.14096	0.14095	0.00000	0.00000	0.00000	0.00000
	GDR-b	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.14368	0.17327	0.14792	0.22005	0.17921	0.00000	0.00000	0.00000	0.00000
	CR-a	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.21444	0.20590	0.25433	0.19074	0.17921	0.00000	0.00000	0.00000	0.00000
	CR-b	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.24370	0.25863	0.22631	0.19683	0.22220	0.00000	0.00000	0.00000	0.00000
Energy	RIECI (E1)	0.25000	0.50000	0.50000	0.25000	0.33333	0.33333	0.00000	0.00000	0.16667	0.16667	0.00000	0.33333	0.33333	0.00000	0.00000
	OECI (E2)	0.75000	0.50000	0.50000	0.75000	0.66667	0.66667	1.00000	0.00000	0.83333	0.83333	1.00000	0.66667	0.66667	0.00000	0.00000
Cost	RICI (C1)	0.50000	0.25992	0.41260	0.22112	0.50000	0.28094	0.00000	0.00000	0.63699	1.00000	0.00000	0.25000	0.49339	1.00000	1.00000
	RTC (C2)	0.25000	0.41260	0.32748	0.31892	0.25000	0.25525	0.00000	0.00000	0.10473	0.00000	0.00000	0.00000	0.19580	0.00000	0.00000
	OCI (C3)	0.25000	0.32748	0.25992	0.45996	0.25000	0.46382	1.00000	1.00000	0.25828	0.00000	0.00000	0.75000	0.31081	0.00000	0.00000
Comfort	Comfort (T)	0.00000	1.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Access	Lift (A)	0.00000	1.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	1.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Safety	Light (S1)	0.00000	0.00000	0.00000	1.00000	0.00000	0.50000	0.00000	0.00000	0.50000	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000
	Smoke (S2)	0.00000	1.00000	0.00000	0.00000	0.00000	0.50000	0.00000	0.00000	0.50000	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000

Table 5.26: Weighted supermatrix

Cluster	Nodes	Retrofit Scenario						Energy		Cost			Comfort	Access	Safety	
		RSR-a	RSR-b	GDR-a	GDR-b	CR-a	CR-b	RSR-a	RSR-b	GDR-a	GDR-b	CR-a	CR-b	RSR-a	RSR-b	GDR-a
	RSR-a	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04089	0.04947	0.02777	0.03024	0.09370	0.00000	0.00000	0.00000	0.00000
RS	RSR-b	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.03845	0.04967	0.01466	0.02675	0.10672	0.00000	0.00000	0.00000	0.00000
	GDR-a	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.05106	0.06114	0.03113	0.03195	0.10147	0.00000	0.00000	0.00000	0.00000
	GDR-b	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04705	0.07667	0.02929	0.04987	0.12901	0.00000	0.00000	0.00000	0.00000
	CR-a	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.07022	0.09111	0.05036	0.04323	0.12901	0.00000	0.00000	0.00000	0.00000
	CR-b	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.07981	0.11444	0.04481	0.04461	0.15996	0.00000	0.00000	0.00000	0.00000
	RIECI (E1)	0.06875	0.03616	0.13751	0.02771	0.09167	0.02411	0.00000	0.00000	0.01284	0.01470	0.00000	0.16667	0.08333	0.00000	0.00000
Energy	OECI (E2)	0.20627	0.03616	0.13751	0.08314	0.18335	0.04822	0.25992	0.00000	0.06422	0.07350	0.28014	0.33333	0.16667	0.00000	0.00000
	RICI (C1)	0.36249	0.04956	0.29913	0.06462	0.36249	0.05356	0.00000	0.00000	0.11290	0.20286	0.00000	0.12500	0.37004	1.00000	1.00000
Cost	RTC (C2)	0.18124	0.07866	0.23742	0.09320	0.18124	0.04867	0.00000	0.00000	0.01856	0.00000	0.00000	0.00000	0.14685	0.00000	0.00000
	OCI (C3)	0.18124	0.06244	0.18844	0.13441	0.18124	0.08843	0.41260	0.55751	0.04578	0.00000	0.00000	0.37500	0.23311	0.00000	0.00000
Comfort	Comfort (T)~	0.00000	0.22681	0.00000	0.00000	0.00000	0.22681	0.00000	0.00000	0.12628	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Access	Lift (A)	0.00000	0.12077	0.00000	0.00000	0.00000	0.12077	0.00000	0.00000	0.21070	0.24115	0.00000	0.00000	0.00000	0.00000	0.00000
	Light (S1)	0.00000	0.00000	0.00000	0.59691	0.00000	0.19472	0.00000	0.00000	0.10535	0.12058	0.00000	0.00000	0.00000	0.00000	0.00000
Safety	Smoke (S2)	0.00000	0.38944	0.00000	0.00000	0.00000	0.19472	0.00000	0.00000	0.10535	0.12058	0.00000	0.00000	0.00000	0.00000	0.00000

Table 5.27: Limit supermatrix

Cluster	Nodes	Retrofit Scenario						Energy		Cost			Comfort	Access	Safety	
		RSR-a	RSR-b	GDR-a	GDR-b	CR-a	CR-b	RSR-a	RSR-b	GDR-a	GDR-b	CR-a	CR-b	RSR-a	RSR-b	GDR-a
RS	RSR-a	0.02850	0.02850	0.02850	0.02850	0.02850	0.02850	0.02850	0.02850	0.02850	0.02850	0.02850	0.02850	0.02850	0.02850	0.02850
	RSR-b	0.02746	0.02746	0.02746	0.02746	0.02746	0.02746	0.02746	0.02746	0.02746	0.02746	0.02746	0.02746	0.02746	0.02746	0.02746
	GDR-a	0.03216	0.03216	0.03216	0.03216	0.03216	0.03216	0.03216	0.03216	0.03216	0.03216	0.03216	0.03216	0.03216	0.03216	0.03216
	GDR-b	0.03841	0.03841	0.03841	0.03841	0.03841	0.03841	0.03841	0.03841	0.03841	0.03841	0.03841	0.03841	0.03841	0.03841	0.03841
	CR-a	0.04506	0.04506	0.04506	0.04506	0.04506	0.04506	0.04506	0.04506	0.04506	0.04506	0.04506	0.04506	0.04506	0.04506	0.04506
	CR-b	0.05165	0.05165	0.05165	0.05165	0.05165	0.05165	0.05165	0.05165	0.05165	0.05165	0.05165	0.05165	0.05165	0.05165	0.05165
Energy	RIECI (E1)	0.03015	0.03015	0.03015	0.03015	0.03015	0.03015	0.03015	0.03015	0.03015	0.03015	0.03015	0.03015	0.03015	0.03015	0.03015
	OECI (E2)	0.11824	0.11824	0.11824	0.11824	0.11824	0.11824	0.11824	0.11824	0.11824	0.11824	0.11824	0.11824	0.11824	0.11824	0.11824
Cost	RICI (C1)	0.21491	0.21491	0.21491	0.21491	0.21491	0.21491	0.21491	0.21491	0.21491	0.21491	0.21491	0.21491	0.21491	0.21491	0.21491
	RTC (C2)	0.04278	0.04278	0.04278	0.04278	0.04278	0.04278	0.04278	0.04278	0.04278	0.04278	0.04278	0.04278	0.04278	0.04278	0.04278
	OCI (C3)	0.15113	0.15113	0.15113	0.15113	0.15113	0.15113	0.15113	0.15113	0.15113	0.15113	0.15113	0.15113	0.15113	0.15113	0.15113
Comfort	Comfort (T)~	0.04508	0.04508	0.04508	0.04508	0.04508	0.04508	0.04508	0.04508	0.04508	0.04508	0.04508	0.04508	0.04508	0.04508	0.04508
Access	Lift (A)	0.06515	0.06515	0.06515	0.06515	0.06515	0.06515	0.06515	0.06515	0.06515	0.06515	0.06515	0.06515	0.06515	0.06515	0.06515
Safety	Light (S1)	0.06078	0.06078	0.06078	0.06078	0.06078	0.06078	0.06078	0.06078	0.06078	0.06078	0.06078	0.06078	0.06078	0.06078	0.06078
	Smoke (S2)	0.04855	0.04855	0.04855	0.04855	0.04855	0.04855	0.04855	0.04855	0.04855	0.04855	0.04855	0.04855	0.04855	0.04855	0.04855

4) Synthesis and finding the priorities

Finally, the three super matrices can enable the command "Synthesize" and then "Computations" to list the priorities of retrofit scenarios (as alternatives) and find the best choice, as shown below in Figure 5.23 and Table 5.28:

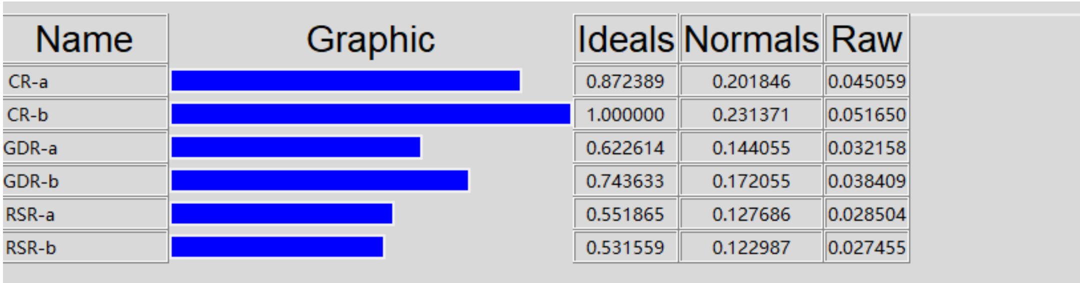

Figure 5.23: Synthesised priorities based on the ANP supermatrix results

Table 5.28: Synthesised retrofit scenario priorities

Name	Ideals	Normals	Raw
CR-a	0.872389	0.201846	0.045059
CR-b	1.000000	0.231371	0.051650
GDR-a	0.622614	0.144055	0.032158
GDR-b	0.743633	0.172055	0.038409
RSR-a	0.551865	0.127686	0.028504
RSR-b	0.531559	0.122987	0.027455

It is found from the ANP synthesised priorities that the cooperative retrofit scenario CR-b is proven as the most appropriate scenario among the six alternative retrofit designs with CR-a following as the second priority for RURB. Also, the RSR-b scenario was given the lowest priority compared with other retrofit scenarios, which should be considered during the decision-making about relevant retrofit designs.

5.8. Summary

This chapter presented the design, modelling, and assessment of the RURB case study in Chongqing City, China. It combined the fundamental 'before-retrofit stage' and 'after-retrofit' stage to become a coherent stream within a positivist framework to establish the case study experiment.

Firstly, this chapter presented how the 'before retrofit stage' of old urban residences is obtained. Sections 5.2 and 5.3 of this chapter identify the realistic situation of existing old urban residential buildings. Secondly, the field survey method was designed and applied in the case study area, with a scoring method established based on the green building assessment tools to quantify the 'old degrees' of old urban residences. Thirdly, the K-means clustering method was adapted to classify the surveyed buildings using 'old degree' data into four different reference building types, based on the building floor numbers, external window types and the 'old degree' scores. As a result, the current circumstances of old urban residences could be fully described with a more reliable data source for the later modelling and design of RURB.

Section 5.4 of this chapter explained the design process of retrofit scenarios to classify old residence types. The design principles referred to the system interactions between system variables and system players, which were discussed in Chapter Four. By reviewing the current literature and documents and analysing the data collected from the social survey, the concepts of the library of possible retrofit measures, degree limits and global limits are developed for the later design of retrofit scenarios.

Generally, there were four types and a total of seven scenarios designed - one baseline scenario to describe the current built environment of old urban residences, with three different scenarios: RSR, GDR and CR models on behalf of the isolated residents, isolated RURB policymakers and the ideal scenario in which all four system players cooperate for the best compromise retrofit plan. Specifically, each RSR, GDR and CR model has been divided into two sub-scenarios following the limitations on the affordable budget and the strength of local government support for RURB. In the next chapter, the retrofitting process of selected old urban residences in the case study area using the building energy simulation method provides a calculation of the retrofit benefits and costs.

Next, the Building Energy Modelling (BEM) based on building simulation tools was adapted as the research method to achieve the retrofitting process and obtain the retrofit results based on designed retrofit scenarios. The annual operating energy consumption intensity data is hence simulated from the BEM platform of the EnergyPlus engine. Afterwards, the other quantitative retrofit criteria were calculated including investment in energy and cost, time cost and operating cost.

Finally, since the data obtained from the retrofit results were both quantitative (as energy and cost) and qualitative (as improvements in comfort, accessibility and safety), the nature of these criteria requires complex network relationships. It is difficult to compare and select the best design since one single retrofit scenario may have many retrofit measures with both positive and negative influences on different retrofit criteria. In this case, the MCDM tool of the ANP method was applied to evaluate all the retrofit scenarios as alternatives. The results of the synthesised priorities were obtained based on the Delphi approach in which local RURB professional experts evaluated the importance of pairwise comparisons from the case study.

6. Discussion

6.1. Introduction

This chapter discusses the results, findings, and reflections on the literature review chapter of both the developed RURB system thinking theory from SPA and CLD methods and the assessed retrofit benefits and costs from the case study BEM process. In the first section, according to the results of Chapter Four, the findings from the SPA and CLDs have developed a systematic theory to describe and understand the RURB system comprehensively and objectively. It can be summarised and discussed in three sections: understanding, problems, and possible solutions.

Next, while the theoretical basis has been discussed, in the case study condition, as the best scenario has been obtained from the MCDM method, the evidence has now been acquired to support the suggestions for future RURB design, decision-making, and policymaking. In this section, the results of the RURB retrofit criteria and their connections between the designed retrofit scenarios and RURB system theory are argued through correlation analysis and discussion.

6.2. Understanding the correct function of RURB policy

At its foundation, the correct functioning of RURB policy comes from comparing RSR and GDR models. From the literature review section, the importance and lack of policy content for RURB (summarised as “less attention” and “low reliability” in Chapter Two) were argued by Han et al. (2021), and it is now proven that the administration of RURB policy is less stable than other building policies such as mandatory building regulations and design standards. The residents’ SPA shows that residents are the final decision makers who have the supreme right to decide or reject any retrofit work which may influence their property. Therefore, it is inefficient for the government to set any mandatory rules and force residents to retrofit or accept unwanted changes to their homes, which cannot change the causal links but may cause serious social problems such as strikes and unrest. This means that communication and persuasion, along with attractive subsidies and/or helpful support, offer a better approach during the development of RURB.

Accordingly, the balancing loop B2 of the GDR model proves that RURB policymaking quickly meets a barrier if it follows mandatory regulations and standards similar to those required for new and public buildings, which was criticised from the policy review by Han et al. (2021) and Zhang and Wang (2013). Following the policy development perspective highlighted by Li and Shui (2015), it shows that the RURB policy should be a service-oriented encouragement guide to develop the retrofit following the demands of residents such as improved indoor comfort, accessibility, and well-being, with financial subsidies to support their top-down administrative strength.

6.3. Revealed systemic problems in the RURB system

There are three systemic and objective problems revealed from the CLDs as constant balancing loops, causal links with contradictory relationships, and operating costs:

Constant balancing loop to residents: The three CLD models reveal that economic issues are currently the most difficult problem for policymakers and residents, as the constant negative effect of ‘retrofit investment cost → residents’ is indicated in Figure 6.1. This constant loop persistently hinders the DDMR of residents in all three CLD models no matter how the professionals' input supports the system. Since all four system players also have their economic issues shown in the SPA result, such issues are theoretically identified as the most serious systemic problem in RURB development. As a constant balancing loop, the priority to identify solutions on this point should address the retrofit cost burden on residents followed by the individual economic issues affecting the other groups of professionals, which was also found and discussed by Jiang et al. (2020) during their survey research.

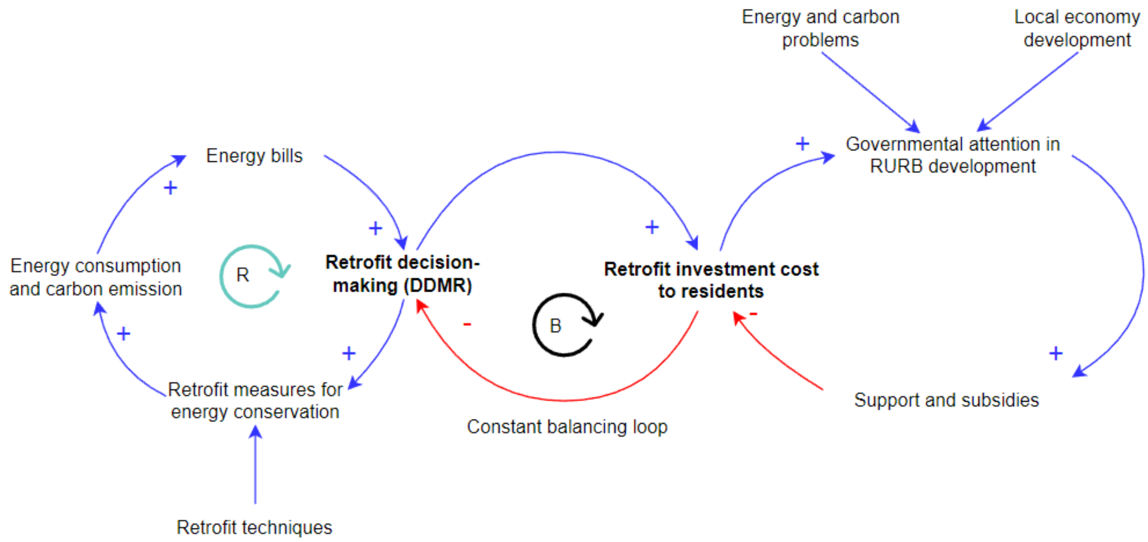

Figure 6.1 Constant balancing loop of retrofit investment cost to residents

Contradictory non-loop flows between energy and comfort: CLD models have also revealed several conflicting non-loop effects which have negative impacts on the system (S. Kim et al., 2021), shown as hindering the DDMR of residents. As shown in Figure 6.2, flows linked with energy consumption and carbon emission present a conflict of contradictory demands between RURB policymakers and residents. Retrofit benefits will constantly increase indoor energy consumption and carbon emissions resulting from the introduction of more HVAC equipment and the advanced retrofit measures can only relieve part of this pressure. From the ROIDF demand of SPA, the government's view is that retrofitted old residences should have lower carbon emissions and energy consumption to achieve the relevant national or international objectives caused by the energy and climate crises. However, in the view of residents, the priority of a retrofit is to acquire a more comfortable private indoor thermal environment to improve their quality of life, happiness, and productivity, which reflects the results from the improvement of the national economy level stated by Xu et al. (2013) and Lin et al. (2016).

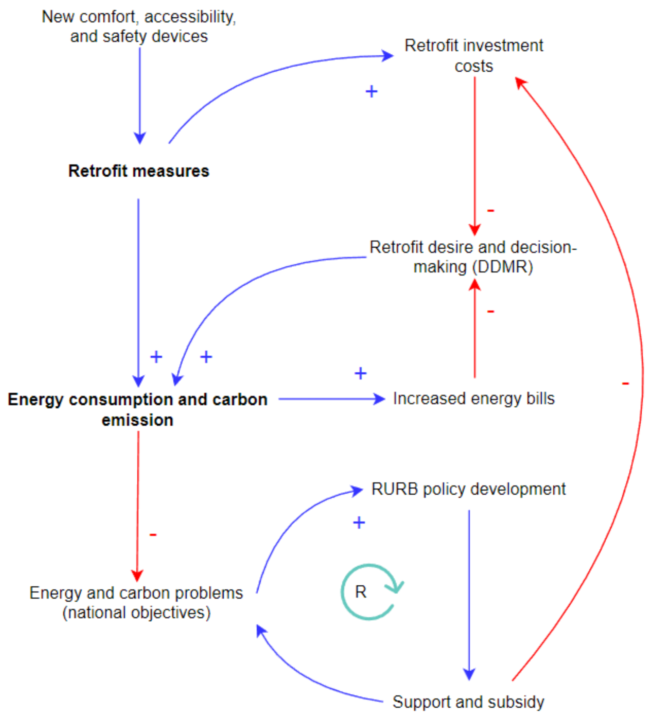

Figure 6.2: Contradictory non-loop flows hinder DDMR between policymakers and residents

Operating cost as energy bills: Building operating costs from energy bills have even more complicated interactions with other variables in the CLDs. The N5 flow in the RSR model, as well as the R1 and R2 loops in the CR model, shows a similar conflict between thermal comfort and energy bills. It shows that policymakers demand the reduction of energy consumption, while residents demand new comfort, accessibility, and safety devices which may unavoidably increase energy consumption. This kind of conflicted causal links can be relieved by advanced (as win-win measures from SPA) retrofit measures provided by scholars from the survey result, such as the replacement of old windows. Yet it can still be a difficult challenge due to the limited usage and the small number of suitable measures that match the local conditions. As a result, this systemic problem requires the development of both RURB policy and techniques that relieve these contradictory loops - since the assumptions of the CR model suppose the subsidy to be large and the techniques well-developed and widely applied.

6.4. Priority of possible solutions

The developed RURB system theory may discuss, propose, and prioritise three important possible solutions for the systemic problems revealed by CLDs:

Distribution of governmental support and subsidy: Since the economic issue of retrofit costs is the most important systemic problem of RURB, the possible solution could be carefully using the limited retrofit budget to satisfy the higher priority of retrofit demands identified from the questionnaire, to avoid the inefficiency risk stated by Pan and Pan (2019). The government should conduct a mandatory survey of residents to obtain their retrofit demands before making a RURB policy or plan. As shown in the SPA results of residents, a prior survey can identify the realistic and urgent retrofit demands and enable the scientific use of tight retrofit funds and improve their cost performance to meet the demands that matter the most.

For example, if the survey results indicated a significant number of elderly residents with low incomes and mobility are living in the surveyed old urban residences, then a lift and accessibility retrofit should be the priority among retrofit measures (Hirvonen et al., 2022). Likewise, if residents report serious hidden risks or hazards from fire, collapse or electric and water leakage, the relevant repair and maintenance retrofit measures should become the higher priority before thermal comfort improvements (Liu et al., 2018b). This means that the limited government support funding should be distributed according to real local conditions and urgent retrofit demands.

As the CR model requires enhanced forms of subsidy to reinforce the system, it is important for policymakers to scientifically design appropriate regulations and distribute limited funds. Some energy efficiency mechanisms may be inappropriate based on the conditions of old residential buildings (Zhou et al., 2013). For example, scholars' SPA shows that the traditionally developed energy management contract (EMC) mode is not suitable for residential buildings. As Jiang (2021) argued, the RURB policy should take various steps to reduce and/or control energy bills by encouraging residents to accept a building façade retrofit and more energy-efficient HVAC equipment. For example, the government can provide a discount to the HVAC equipment market with a subsidy to recycle old, inefficient, heating, and cooling equipment.

For energy bills - the third systemic problem of RURB, policymakers should also carefully reconsider the step tariff method, as the questionnaire survey results show it is unpopular with residents. As discussed by Alam et al. (2019), it is still possible for policymakers to set limitations to encourage residents not to use too luxurious heating and cooling devices such as central cooling and district heating in the HSCW climate zone since they have proven less popular than split devices in the thermal comfort survey.

Selection of retrofit techniques: As solutions for contradictory loops between better living quality and energy bills, the scholars' output provides the most important contribution to relieve the conflict in the CR model. Although the SPA result shows that different RURB system players have their individual opinions, comments, and preference for retrofit measures, it appears that the 'external window' retrofit is the keyword most frequently mentioned by all four system players. It shows that advanced win-win retrofit techniques exist (or can be developed in the future by scholars) to solve the systemic problems of conflicted loops by simultaneously achieving both energy conservation and improving indoor comfort.

Local conditions: For the issue of "single building scale" criticised in Chapter Two, as shown in the CR model, a significant local advantage can break the barriers isolating residents and scholars, improve effectiveness and enhance economic benefits through adopting advanced retrofit measures, which was mentioned by Hargreaves et al. (2017) and Mastrucci et al. (2014) as unique possible findings from urban-scale studies. Especially, understanding local conditions can suggest many advantages including preferences for retrofit measures, energy use behaviours, living habits, local energy resources and local economic features. Yet these factors have usually been ignored in previous RURB policies, projects and studies over many years (Cao et al., 2016). Therefore, regarding the demands of the residents' SPA as their true desires and correctly ordering the priority preference levels of retrofit measures based on local conditions is the key to reinforcing residents' DDMR and RURB efficiency.

6.5. Correlation analysis and Payback Period (PBP) in the case study

1) Between retrofit investment energy consumption and costs

The argument of correlations between RIECI, RICI and RTC reflects the cost performance of selected retrofit measures. The attributes of the three factors are all 'costs' of energy, economic costs, or time, which can be classified as 'negative influence factors' on RURB. In this study, a variety of retrofit measures and new equipment and devices are introduced into old urban residence models to improve energy efficiency, living quality and the indoor environment. Reflecting the "oversimplification" problem mentioned in Chapter Two, using life-cycle energy consumption thinking in residential buildings by Zhu et al. (2018) and Cao et al. (2017) shows that the production processes of these materials and equipment introduce concerns about high energy consumption and carbon emissions, while this one-off energy use from material and transportation is usually neglected in similar BEM studies.

On the other hand, the initial one-off retrofit investment cost is the biggest concern to the residents – the questionnaire results showed RICI is much more important than OCI in the view of residents during the consideration of RURB decision-making, as well as the first systemic problem found in CLD section. Therefore, RIECI, RICI and RTC should lie within a reasonable and affordable range regarding the concepts of degree limit and global limit. Their correlation can show the conditions of all negative influences during the RURB development, as in Figure 6.3.

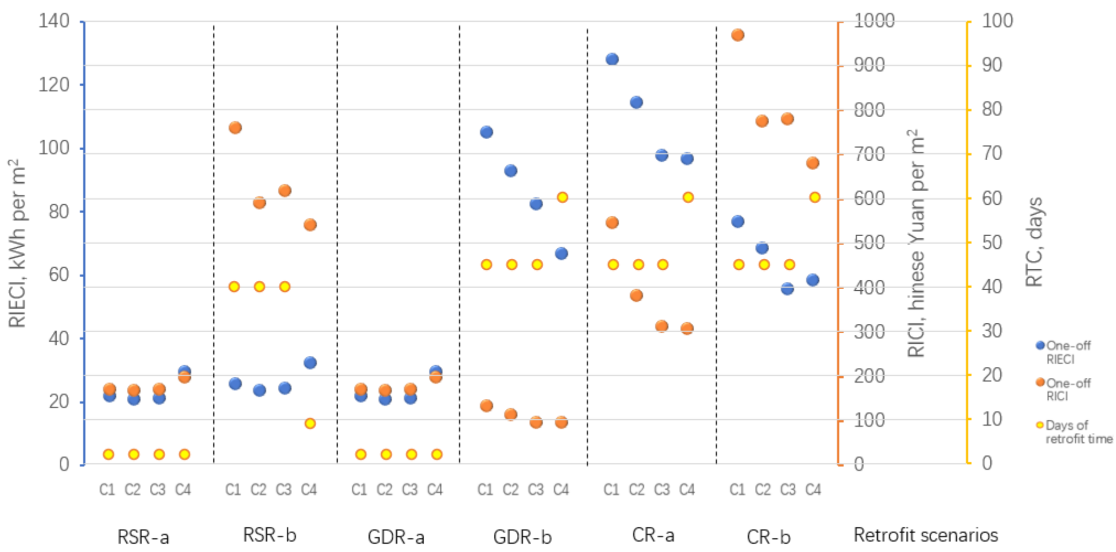

Figure 6.3: Correlations between RIECI, RICI, and RTC as negative cost influences

RIECI is found not to be closely relevant to either RICI or RTC due to its nature as a heavy construction material and transportation energy use (Mastrucci et al., 2017). The RIECI reaches its highest value in the GDR-b and CR-a scenarios while the RICI was comparatively low due to the selection of a cheap insulation technique for external walls - APG mortar - rather than the expensive EPS or XPS in CR-b.

For RICI as the most important retrofit cost, a feature of RSR-a and GDR-a is that they involve only a few retrofit techniques, hence the RIECI and RTC are closely related to RICI and all three are low value. For RSR-b and CR-b scenarios, however, the comprehensive retrofit measures that were added, such as lifts, have significantly increased the total RICI and RTC due to the construction difficulties in lift installation and external wall retrofit. Although the RTC now reaches a high value of 45 to 60 days, the RIECI is still not closely influenced, which suggests that the production and transportation energy consumption for lifts and new devices are very moderate and might not be necessary for the analysis - compared to the high purchase price of these features.

2) Energy payback period from the correlation between RIECI and OECI

According to the retrofit design, the retrofit techniques for a building's external façade are the factor most likely to influence the RIECI due to the large amount of insulation and construction materials required. As feedback benefits, insulation and the replacement of windows can also achieve considerable OECI savings by passively increasing indoor thermal resistance and air tightness. Yet from the building life-cycle assessment (LCA) perspective, the one-off investment energy RIECI should be considered as an important value since the building materials and transportation may require industrial energy consumption and produce pollution (Zhu et al., 2018). As this RURB research conforms to a 30-year length as the retrofit frequency, the annual OECI is multiplied 30 times to obtain the energy payback period analysis for RIECI, as in Figure 6.4.

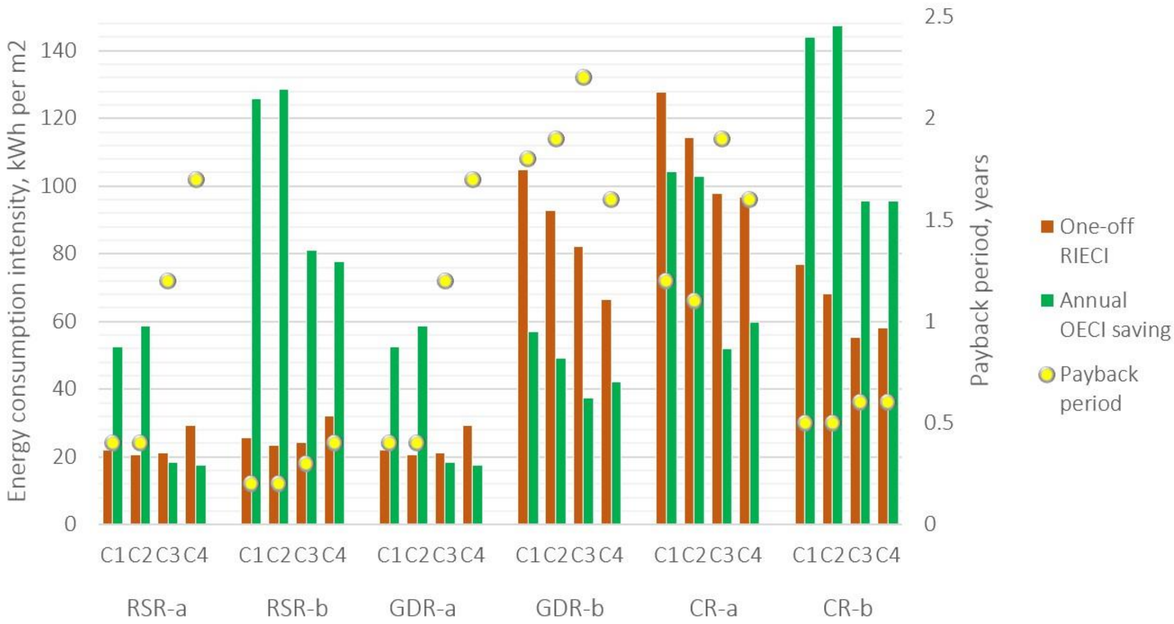

Figure 6.4: Correlation between RIECI, annual OECI, and retrofit energy payback period

Overall, it is found that the RIECI is not much higher than the OECI for even one year, in most retrofit scenarios. The RIECIs are within the range of only 20% to up to 220% of the annual OECI, from 0.2 to 2.2 years to pay back the investment energy from the OECI saved by the retrofit measures. In this case, the maximum investment energy payback period is the GDR-b scenario for old apartment (cluster 3, 10 floors) type residences at only 2.2 years (802 days) while the minimum investment energy payback period located on the RSR-b scenario for dilapidated apartments (cluster 2, 8 floors) is even less at 0.2 years (as 67 days).

A sensitivity analysis is given for the two higher RIECI retrofit scenarios: GDR-b and CR-a. Reflecting the retrofit settings and materials embodied energy data in Chapter Five, it shows the higher energy consumption during the production of cheap APG mortar compared to the more expensive EPS and XPS insulation layers. Meanwhile, the high annual OECI saving from RSR-b and CR-b has proven the retrofit effectiveness of Low-E windows and the introduction of the hot water radiator system with natural gas boilers. Under these two retrofit scenarios, the RIECI is found not worthy of mention with an average of 0.2 to 0.6 years payback period. As a result, the RIECI should not be considered an important negative influence factor in any case during the consideration of passive energy efficiency designs.

3) Cost payback period from the correlation between RICI and OCI

Similarly, the OCI is closely related to RICI as the higher energy efficiency HVAC equipment can significantly reduce the OCI, but their purchase prices on the market are also higher, which increases the average RICI. Compared to the RIECI and OECI, the cost issues are a much more important negative influence factor on the views of both RURB policymakers and residents due to the nature of their actual economic demands (Hong et al., 2016). As a result, the longer payback period of RURB is a concern for the argument about encouraging residents to decide retrofit. In this case, the RICI and OCI data should be analysed as in Table 6.1 to show how many years it will take for the energy saved from the retrofit designs to recover the initial one-off investment cost.

Furthermore, as indicated before, the payback period of OCI is highly related to the local prices of energy resources, equipment on the market and construction labour rates. By reviewing the national resource pricelist, the prices of construction labour, electricity, and natural gas for residential building use in the case study area of Chongqing city are comparatively cheaper than in mega-cities (such as Shanghai) or developed countries (Chongqing city Bureau of Statistics, 2019), but the equipment prices remain the same. Under this circumstance, it can be assumed that the cost payback from OCI savings may require a longer time to earn the investment cost return.

Table 6.1: The payback period between RICI and OCI saving

RS	Cluster 1 (6F): Dilapidated Apartment			Cluster 2 (8F): Dilapidated Apartment			Cluster 3 (10F): Old apartment			Cluster 4 (30F): Old tower		
	One-off RICI	Annual OCI saving	PBP	One-off RICI	Annual OCI saving	PBP	One-off RICI	Annual OCI saving	PBP	One-off RICI	Annual OCI saving	PBP
	kWh/m2	kWh/m2 • year	Year	kWh/m2	kWh/m2 • year	Year	kWh/m2	kWh/m2 • year	Year	kWh/m2	kWh/m2 • year	Year
RSR-a	169.5	8.6	19.7	166.4	9.7	17.2	169.9	3.0	56.6	197.5	2.9	69.1
RSR-b	759.6	20.2	37.6	590.6	20.7	28.5	617.4	13.0	47.5	539.7	12.4	43.6
GDR-a	169.5	8.6	19.7	166.4	9.7	17.2	169.9	3.0	56.6	197.5	2.9	69.1
GDR-b	131.7	9.4	14.0	113.6	8.1	14.0	96.4	6.2	15.5	95.4	6.9	13.8
CR-a	545.1	17.1	31.9	382.3	16.9	22.6	312.1	8.6	36.3	306.4	9.8	31.3
CR-b	969.3	23.4	41.4	774.1	24.1	32.1	778.8	15.6	49.9	680.1	15.6	43.6

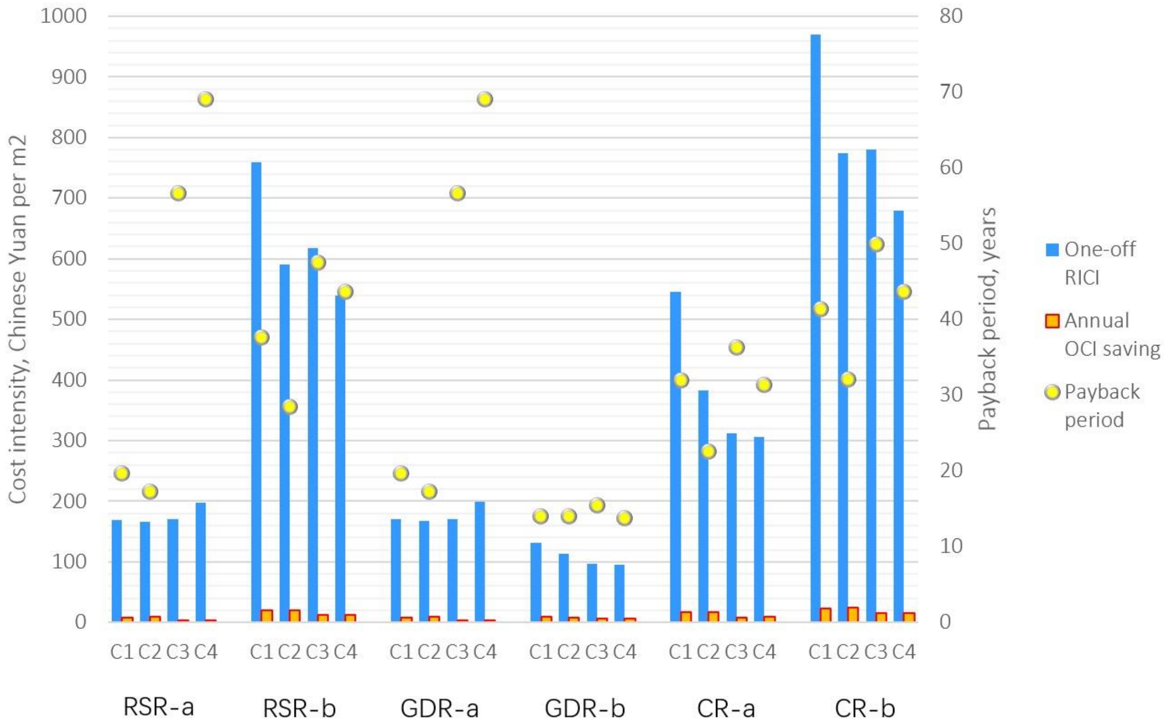

Figure 6.5: Correlation between RICI, annual OCI, and retrofit cost payback period

Surprisingly, the situation of the cost payback period is much more extreme compared to the energy payback period. As indicated, the OCI savings with low prices of energy resources account for a very small share of RICI (the orange area above Figure 6.5) which is hardly recognised using the same left y-axis. Assuming the energy prices remain constant, at least 13.8 years are required to return the retrofit investment cost in the GDR-b scenario of C3: the old apartment-type residence. Then an incredibly long time of up to 69.1 years in the RSR-a and GDR-a scenarios of C1: the dilapidated apartment type (6 floors) residences, which makes the payback highly impracticable.

In general, there are 14 of the total 24 retrofit cases and 58.3% of them have a cost payback period of over 30 years, which is longer than the maximum LCA time for the retrofit. It shows that many retrofit scenarios cannot earn money back from the OCI savings within the cycle of one-time retrofitting. This result has again raised concerns over the conflict between national energy conservation objectives and residents' increasing demands and the pursuit of better indoor thermal comfort and living quality. Looking at the GDR-b scenarios which were designed only to reduce the OECI by retrofitting the building's external façade, they have the shortest cost payback period (13.8 to 15.5 years) since there are no additional energy-consuming devices introduced.

It is understandable that considering the nature of applied retrofit techniques to provide qualitative improvements (such as lifts, air purifiers, public space lighting and indoor smoke detectors), they not only increase energy consumption, which increases the operating cost, but they are also comparatively expensive to purchase. Therefore, in the case study, it is very difficult for residents to pay the investment cost back only counting on operating cost savings by energy conservation from building façade retrofit and HVAC equipment. It can be inferred that a corresponding governmental subsidy will be necessary and useful to reduce RICI and motivate residents.

6.6. The CR-b: 'The best' retrofit scenario from MCDM analysis

As indicated above, the MCDM analysis of the ANP method developed in this study has shown that the comprehensive Cooperative Retrofit (CR-b) scenario is the best retrofit design package. It has simultaneously met the retrofit demands and features of all four RURB system players to achieve both the highest retrofit benefits but also has the highest retrofit costs. The retrofit criteria details of CR-b are summarised in Table 6.2:

Table 6.2: Details of CR-b retrofit scenario

Criteria			Unit	Cluster 1 (6F): Dilapidated Apartment	Cluster 2 (8F): Dilapidated Apartment	Cluster 3 (10F): Old apartment	Cluster 4 (30F): Old tower
RIECI	◆	Total	kWh/m^2	76.8	68.2	55.4	58.2
OECI	◆	HVAC	kWh/m^2	26.8	24.3	23.8	26.8
	◆	Total	kWh/m^2	100.8	97.9	98.0	97.2
RICI	◆	Resident pay	CNY/m^2	659.0	523.0	545.0	492.0
	◆	Government pays	CNY/m^2	303.0	245.0	227.0	182.0
	◆	Transportation	CNY/m^2	7.3	6.1	6.8	6.1
	◆	Total	CNY/m^2	969.3	774.1	778.8	680.1
RTC	◆	Total	days	45	45	45	60
OCI	◆	HVAC	CNY/m^2	4.7	4.2	4.1	4.5
	◆	Total	CNY/m^2	16.8	16.2	16.2	16.1

The CR-b scenario can hence be detailed and discussed reflecting the ROIDF results analysed using the SPA method with all four RURB system players for future RURB decision-making and policymaking:

Residents: Quantitatively, residents who live in old urban residences need to pay a comparatively high price for the retrofit investment at 492 to 659 CNY per m^2 from residents and 182 to 303 CNY per m^2 support by the government. This provides the highest energy conservation – the remarkable saving ratios will be 86.1% to 90.1% in the HVAC energy sector and 49.4% to 60.1% in total energy. Following the introduction of new equipment and the price gaps between energy and retrofit measures, the benefit of the reduced energy bill is hence moderate – a 25.1% to 29.4% reduction in the total energy bill.

Qualitatively, residents can benefit from the maximised improvements in indoor comfort and living quality, including more comfortable winter heating strategies, reduced air infiltration and noise issues because of the new insulation windows, healthy indoor air quality from air purifiers, much better accessibility from the new lifts, reduced falling risks in dark public spaces and lower fire risks from the deployment of smoke detectors.

Designers and engineers: Designers determine the library of possible retrofit measures and select the appropriate techniques based on the global limits and degree limits obtained from the interview and questionnaire survey results in the case study area. According to the retrofit scenario design section, the ideal CR-b scenario has the most, and the most expensive, retrofit measures applied to old urban residences. For the retrofit measures with the same effectiveness but different prices, advantages and disadvantages, the engineers can benefit from the selection of more advanced, easy-to-construct and easy-maintenance techniques with longer guarantee periods, such as to use of advanced XPS insulation to replace the APG mortar for walls and roofs.

Scholars: The guidance from scholars is embodied in the selected advanced retrofit measures, including Low-E double silver-plated windows, an improved insulation U-value index for external walls and roofs (compared to the current BEES) and new inner sunshade Venetian blinds in the CR-b scenario. These selections had been tested and evaluated according to local climate conditions and local advantages by relevant sensitivity and optimization studies and been found appropriate for the residential buildings in the case study area.

Policymakers: The CR-b scenario has received very strong support from the local government in various forms, including the 'completely covered' 40 to 60 days of construction engineering and materials for the external wall and roof retrofit and public space lighting retrofit or update. Further, an HVAC equipment discount of 400 CNY each and one-off subsidies of 100,000 CNY per lift installation and 25 CNY per m^2 of total household area. Only the discount on the energy price was not considered as support content due to the low energy price at the time of the research. As a result, the government will take on around 26.8% to 31.3% of the total retrofit investment cost (182 CNY per m^2 to 303 CNY per m^2 depending on the type of residence), to achieve a final OECI reduction of 49.4% to 60.1% of the total energy consumption to achieve their political objectives required by national policy.

In addition, the CR-b retrofit scenario has provided a valuable and representative template for RURB policymakers. It shows the most ideal retrofit benefits and costs in the urban area, and it can be further calculated based on statistical data to present the total energy conservation potential in the urban district or even the whole city level, as well as the total economic budget requirement from the local government.

6.7. Possible use of other retrofit scenarios

Although the CR-b scenario was evaluated as the best retrofit scenario, the other scenarios designed in this research can still be useful under different local conditions.

The design principles of the RSR-a and the GDR-a models represent the condition where residents have a very limited economic ability or desire to pay for retrofit costs. The total RICI could be very cheap at 166 to 198 CNY per m^2. Yet these very basic retrofit scenarios can still provide 12.5% to 30.0% energy and bill-saving on HVAC energy for dilapidated and old apartment buildings. These scenarios should be appropriate for the lower-rise residential buildings located in smaller cities and towns (with GDR-a), as well as in villages and rural areas (with RSR-a) depending on the minimum available support from the local government or community, which is similar to the governmental data from China Association of Building Energy Efficiency (2016).

The GDR-b scenario could be seen as currently the most popular approach used in modern cities in China. As mentioned during the policy and project review section, the 'all-covered by government' thinking in the GDR-b model was very popular with local governments for achieving the national objectives of national policy (usually asking local governments to finish a specific number of demonstration projects or retrofit areas within five years (National Development and Reform Commission, 2016)). With its high effectiveness and sufficient budget, GDR-b can easily be applied to old urban residences since the communication steps with residents can be skipped. In this case, the top-down administrative strength can easily achieve 25.1% to 29.4% HVAC energy consumption reductions by increasing the thermal performance of old external walls and roofs to the current newest BEES index. However, as He et al. (2021) discussed, the decision-making result of the case study may only be suitable for cities located in the HSCW climate zone, and the retrofitting effectiveness of GDR-b can be variable in other climate conditions.

Finally, the ANP results showed that the RSR-b model is “the worst scenario” with the lowest priority among the six alternatives (see Table 5.28). It brings an important insight and warning to the RURB policymakers. As discussed by Yao et al. (2016) and Jiang (2021), the rapidly developed economic level of urban citizens will naturally lead to them retrofitting their indoor environment by introducing more and more equipment and devices and extending their usage to pursue more comfortable lives, as a natural consequence of the RSR-b model. However, following the “global limits” set during the selections of retrofit measures, residents cannot retrofit building insulation of walls and roofs to improve the thermal performance of the building façade. Thus, the total energy consumption of urban residential buildings would be increased under this trend. Therefore, RURB policymakers should act beforehand, such as designing mandatory retrofit BEES before the ‘spread’ of the RSR-b scenario. With the necessary support from the government, the worst RSR-b scenario may be easily converted into CR-a or CR-b and become the most appropriate retrofit scenario.

6.8. The RURB design and BEM reflect the developed system theory

More importantly, the design and BEM of RURB should reflect the research philosophy and system thinking elements argued in Chapter Four. Reflecting on the research questions and research methodology, the established RURB case study presented in Chapter Five aimed to verify the developed RURB system theory from the positivist perspective. Since the retrofit scenario designs reflected the system interactions, it is also necessary to discuss whether the design and BEM process of the case study has accurately and strictly followed the system cognition thereby verifying the rationality of the developed RURB system theory.

1) System definition as current conditions of old urban residences

As the fundamental starting point raised as research question one, the current conditions of old urban residences in the case study have been described in Chapter Five and reflected the defined RURB system definition and system boundary from Dixit et al. (2013) and Pan (2014). Firstly, the field survey and document research provided more realistic data on both the physical conditions and the content of old buildings which were awaiting retrofit. The reliable descriptions of surveyed residential buildings conformed to the system definition of old urban residences. The collected descriptions were scored as 'old degrees' to explain the details and clarify the current circumstances and existing problems.

Secondly, the building typology based on the K-means clustering method from Li et al. (2018b) and Gui et al. (2018) were used to classify the complex building models into four typical reference buildings to describe and represent the basic building information. In this step, the defined local conditions of the system entities were mentioned while the indoor floor plan, number of floors, building façade structures, external window types and "old degree" index were structured to represent the physical building models.

Thirdly, the classified building models were supplemented with detailed constant settings within the RURB system boundary defined in this research, including local weather conditions, thermal comfort requirements, occupant behaviour profiles, usage of residential lighting, plug-in energy, and domestic hot water. This information enhanced the explanation of the system entities obtained from field surveys, reviewed documents, and social survey results. In summary, the integrated research methods applied to establish the RURB models in the case study can be argued as more reliable, which relies on system definition, system boundary, and survey data, rather than using urban statistical data and simplified default parameters from the BEES index.

2) System cognition as retrofit design principles

The established "library of possible retrofit measures", "global limits", and "degree limits" in this study can be interpreted as retrofit design principles. They should be tested by reflecting the results of ROIDF linked to the RURB system cognition obtained from the SPA method.

Roles: The roles of different system players were tagged during the interview and questionnaire survey. The professional RURB policymakers, designers and engineers and scholars are classified as supporters of initiators, enforcers, and proponents to motivate residents to make retrofit decisions, as well as practitioners and advisers on RURB policy and techniques. Similar to the language gap between ‘mandatory’ and ‘suggested’ rules in the design principle of BEES (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2022b), RURB professionals and design principles in this study are comparatively subordinate to residents – because residents will pay the major retrofit fees (exclude the GDR-b) and have the right to decide or deny RURB works. In this case, professionals cannot force residents to take retrofit actions (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2017b).

Outputs: The designed case study and result analysis provided useful information on all types of possible outputs for the four RURB system players. To policymakers and their outputs of retrofit policy, BEES and subsidy, the case study design showed them the required quantity and efficiency of governmental support in different scenarios and how they can achieve energy conservation on an urban scale (as ‘demands’ which will be discussed below). For designers and engineers and their output of retrofit designs, the developed case study is a coherent, detailed, and comprehensive framework and template starting with collecting the current conditions of old urban residences and continuing up to the decision-making analysis of retrofit scenarios.

Meanwhile, for scholars and their outputs of suggestions and techniques, the design principles had taken the academic results from published research into consideration in the selection of retrofit measures - including studies of local advantages and climate-responsive design (as reviewed studies from Cheng and Steemers (2011), López-Pérez et al. (2019) and Yao et al. (2018)) - to make the retrofit design more scientific. In this case, scholars are no longer isolated in the RURB system, and their knowledge and techniques can help achieve greater retrofit effectiveness. To residents, the majority principles for the selection of retrofit measures for energy bill saving, improvements of thermal comfort, accessibility and safety were about to achieve their outputs of happiness, productivity, satisfaction, and increased income (as increased rent or selling price (Zhang et al., 2018)) from RURB.

Issues: The issues among the system players in the case study were identified as fixed, unassailable, global limits as well as flexible, diverse, degree limits. With the issues argued and clarified in Chapter Four, the RURB design in this study endeavoured to minimise the negative influences of issues by selecting the most appropriate retrofit measure within the “global limit” rules as optimization (Gou et al., 2018).

In this case, five issues of residents have already been revealed as 1) Individual preferences for the economic burden; 2) the will towards coordination; 3) arguments over retrofit benefits; 4) arguments over retrofit troubles and 5) lack of motivation. Consequently, the retrofit design principles attempted to solve or relieve these issues, by 1) introducing governmental subsidies as discounts and/or covering the costs of construction engineering; 2) collecting and analysing the residents’ opinions using a questionnaire survey; 3) calculating all the retrofit benefits and making a visual display for analysis; 4) selecting the easy-to-construct and easy-to-maintain retrofit measures within the time cost limit and 5) providing calculated retrofit benefits that save energy, reduce bills and improve living quality.

Demands and Features: The varied identified retrofit demands and relevant features of system players were also considered during the selection process for retrofit measures. To comply with their demands, the design principle was to choose the retrofit measure for its performance at the maximum allowance of “degree limits” from policymakers and residents. To reflect their features, the retrofit design followed the ability, inability and preferences of each system player and included all appropriate retrofit measures in the package following the experience of Jiang et al. (2020) and Hu et al. (2019).

For example, the retrofit demand of policymakers lies in energy consumption and carbon emission reduction, with the feature of top-down administrative support available from the government. Therefore, the design principles for GDR-a and GDR-b scenarios reflected their ability to offer economic support and “full-paid” retrofit construction works for the external walls and roofs. Likewise, the RURB designers and engineers require reliable RURB policy and BEES to reduce their reliance on empirical knowledge. In this case, the retrofit design in Chapter Five was developed based on a systematic theoretical basis to support the applied retrofit techniques, which could be seen as an improved retrofit standard.

6.9. Summary

In summary, the discussion of RURB systemic problems revealed the possible solutions and their priorities for future RURB policymaking, which were discovered and discussed based on the SPA and CLD results. Retrofitting policymakers were suggested to use social survey methods to reasonably distribute the limited government support adapted to local conditions and the urgent demands from residents. Also, the selection of retrofit techniques with consideration of specific local advantages, such as energy price and occupant behaviours, were argued as important factors to improve the efficiency of RURB policymaking and designing.

For the RURB case study in Chongqing City, a comprehensive discussion of retrofit benefits and costs was presented to argue and discuss the findings from the results of energy modelling and cost calculations. The correlations between quantitative retrofit benefits of energy and cost with costs of money and time were analysed as the payback periods for each retrofit scenario. Meanwhile, the selected CR-b retrofit scenario's detailed retrofit benefits and costs are discussed for the retrofit potential on an urban scale, while the possible scope of application for the other designed retrofit scenarios was also argued based on different local conditions. Finally, the coherent case study framework developed in Chapter Five was reviewed and discussed to reflect and verify the rationality of the developed RURB theoretical basis by reflecting on the RURB system definition, system cognition and system interactions.

7. Conclusion

7.1. Introduction

This chapter summarises the key research findings from the above result and discussion chapters, to answer the research questions related to the five research objectives stated in Chapter One, and to reflect the research gap and insights from the literature review as research contributions. The research questions, aims and objectives are stated again and reflected as references for the summarised research arguments and achievements. There were five research objectives mentioned with deliverables, as follows:

1) To explore the current problems and research gaps in the knowledge of RURB policy content, academic studies hence to find the insights based on previous experience.
2) To clarify and understand the RURB system by systematically discovering and analysing the system definition, system cognition, system boundary and participants and their interactions.
3) To clarify and understand the complex system interactions between system participants and variables, causal links, and feedback to find the hidden systemic problems in the current RURB system and possible relevant solutions for RURB design.
4) To develop a research framework to generate reliable data on retrofit results based on both the RURB system's theoretical basis and the realistic data collected from RURB professionals and residents on their retrofit desires and demands, knowledge, retrofit designs with suitable retrofit measures and individual opinions.
5) To evaluate the retrofit benefits and costs of the case study retrofitting results and make decisions for the retrofit plan designed for the local urban area. According to the analysis of decision-making based on retrofit criteria, evidence and suggestions can be obtained to support more scientific future policymaking for RURB.

The methodology adopted to achieve the research objectives above was argued, selected, and framed based on its ability, advantages, and applicability. The RURB theory with a system perspective was developed by identifying and clarifying the system definition, as well as a rich description of RURB system cognition and interactions – by the adapted CLA method of SPA, social surveys and the CLD method. Thereafter, a case study was developed as an experimental platform to verify the hypothesis behind the developed RURB system theory and its rationality by the retrofit design and the BEM and ANP methods of multi-criteria decision-making.

7.2. Main conclusions in respect of the research objectives

In this section, the main arguments and achievements of the thesis are set out according to each research objective.

7.2.1. Research objective one

The first research objective 'to explore the problems and research gap in the current knowledge of RURB policymaking, research and engineering practices' is achieved by the comprehensive review of three types of literature, 1) current governmental policy content and regulations; 2) published academic studies, and 3) RURB project reports of case studies. In this research, the 40-year development history of RURB policy in China, published papers on RURB theory, methods, and techniques, and national RURB yearbooks and international Annex projects are reviewed to understand and discover the current knowledge and problems for the retrofitting of urban residential buildings.

The current research gap is hence addressed by reviewing and arguing the criticisms and insights summarised from the current knowledge, as a "linear engineering perspective" which caused problems including 1) less attention and the low reliability of policy content; 2) research scale and the isolation of current studies; 3) empiricism and the low efficiency of RURB design, and 4) the lack of communication between professionals and residents. These problems become the fundamental basis for the later argument for identifying and understanding RURB by using the necessary system thinking perspective.

7.2.2. Research objective two

The second research objective is achieved by developing a system theory to understand RURB from the system thinking perspective. The conventional linear engineering perspective and subjective interpretivism of RURB are argued and criticised as being unscientific and inefficient. Hence a novel and extendable theoretical framework is presented to assume, justify, and comprehensively explain the complex RURB system by adopting the research methods of inductive reasoning from a Bayesian and positivist system perspective.

In this case, RURB is proposed, justified, and defined as a complex and cooperative system, which is operated by different professionals and residents. Following the positivism logic, the RURB system is objectively stated with a clear system definition and system boundary, rather than as the conventional thinking underpinning a "political task" or "a piece of engineering work". The adapted "system player analysis" (SPA) is then justified as being suitable to clarify and understand the RURB system cognition while thinking this system is played by four groups of people as policymakers, designers and engineers, scholars, and residents. The system cognition is hence comprehensively described and explained based on these four core system players along with five-layered characteristics based on their "Roles, Outputs, Inputs, Demands and Features" (ROIDF) identified as their unique characteristics.

7.2.3. Research objective three

The third research objective is to clarify and understand the complex system interactions within system variables, as "causal links" and "feedback". The complex relationships inside the system are structured based on the defined system boundary and variables, following the SPA results. Three retrofit scenarios are thus developed to represent all the possible cases of the RURB system by applying the CLD method: causal loop diagrams.

The RURB system interactions between all four system players are analysed using the CLD method based on three different retrofitting models related to the main system players (as driving force): 1) the resident spontaneous retrofit model; 2) the government-driven retrofit model, and 3) the cooperative retrofit (as the ideal) model. Their unique interactions between the total of 25 system variables and 4 system players are analysed as reinforcing loops, balancing loops, and non-loop effects. Three systemic problems and possible solutions are then revealed and discussed: 1) cost and limited retrofitting funds, 2) conflict of retrofitting demands between policymakers and residents, and 3) conflict between thermal comfort and energy bills.

7.2.4. Research objective four

The fourth research objective is the verification of the RURB system perspective theory used to develop a coherent research framework to generate reliable data on retrofit results in a designed case study. This objective is achieved by using the adapted and combined research methods of social survey, building typology, field survey, retrofit scenario design and BEM technique.

In Chapter Four, the fundamental data for the RURB design is collected from RURB professionals and residents, as 12 interviews and 1100 questionnaires. Afterwards, in Chapter Five, the case study area is selected based on the established principles for RURB research and the field survey method was applied with a scoring method to quantify the "old degrees" of old urban residences, in Chongqing city, China. Then, the K-means clustering method is adapted to classify the surveyed residences using 'old degrees' information into four different reference building types.

Next, for each building type, one baseline and six retrofit scenarios of RSR, GDR and CR are developed (a total of 28 old residential building models) and designed based on the established concepts with different values, as "library of possible retrofit measures", "degree limits", and "global limits", as well as the system interactions delivered by research objective three. The EnergyPlus platform is used to obtain the annual energy consumption data of all models, and the data of investment energy, costs, and time of construction work are calculated according to the designed parameters and selection of materials.

7.2.5. Research objective five

The fifth and last research objective is to evaluate the retrofit benefits and costs of the case study retrofit results. Based on the complex interactions between system components revealed by the CLDs, the ANP method of MCDM approaches was discussed and applied to evaluate the retrofit results of the designed RURB scenarios from BEM and calculations. According to the defined system variables, the retrofit benefits and costs are quantified and qualified as five retrofit criteria for energy, cost, indoor air quality, accessibility, and safety.

As the achievements of research objective five, the synthesised ANP results from Super Decisions software are used to help system players make decisions on retrofit scenarios designed for the local urban area. Furthermore, from the priority list of ANP results, the reference retrofit design (as six scenarios), evidence of retrofit results and suggestions for retrofit measure selections are justified to support more effective and scientific future design and policymaking for local RURB.

The retrofit benefits and costs from case study models are also presented and discussed to argue and discuss the findings from the results of operating energy simulation and investment energy and cost calculation. Payback periods of energy and costs are obtained by using the correlation analysis between quantitative retrofit benefits with costs of money and time for each retrofit scenario. All the retrofit scenarios are weighted to present their values of retrofit benefits and costs for decision-making. At last, Chapter Six discusses the findings of this research reflected in the literature review section to verify the achievement of current research gaps, which has also argued the rationality of the developed RURB theoretical basis using the developed RURB system definition, system cognition and system interactions in Chapter Four.

7.3. Contribution to the Theory

As the most important contribution to the theory, this thesis argues and discusses the advantages of the use of causal layered analysis adapted with the system thinking perspective and system dynamics, to become a new theory of the system player analysis method to obtain objective system cognition and interactions of a very complex system with different groups of people involved as core participants.

As indicated, the CLA method indicates that a complex system can be understood by defining the participants as layers with four aspects: the litany, system causes, worldview, and myth and metaphor analysis (Inayatullah, 1998). However, this thesis argues the limitations of CLA when the complex system is composed of different groups of individuals and roles with diverse opinions and preferences (Riedy, 2008). Therefore, as an extension based on the defined RURB system components, this research adapts the current CLA into the SPA method. The system core participants involved in the RURB system are identified as four system players and their layered characteristics are defined as Roles, Outputs, Issues, Demands and Features (ROIDF) to be analysed to obtain a rich description of RURB system cognition.

Combined with the general system definition acquired from inductive reasoning and the system interactions from CLD, a coherent systematic theory is developed to provide a new, objective and comprehensive understanding of the system for retrofitting urban residential buildings. The developed theory is supported by both the review of current RURB documents and social survey results. It is then proven by analysing and evaluating the corresponding retrofit scenario design using the BEM method and MCDM analysis. The ANP evaluation result for retrofit scenario priorities verified the rationality and reliability of the developed RURB system perspective theory. This theoretical framework constructed by combining SPA and CLD can be extended to other research fields which have similar complex problems.

7.4. Contribution to the Knowledge

This thesis argues that empiricism is the key problem in current RURB design and engineering using the case in China. Therefore, this thesis considers RURB from the system perspective. Based on this theoretical basis, a coherent methodology framework for RURB design and BEM and retrofit results analysis is developed as a case study by representing the possible and ideal retrofit scenarios of old urban residences. Corresponding to the literature review in Chapter Two, the contribution to knowledge in policymaking and studies can be summarised, as follows:

Policymaking: Since the distribution of limited governmental support is found to be a systemic problem in RURB, this thesis develops an approach that generates sets of data for policymakers to understand and obtain the necessary information on the retrofit potential of old urban residences. Compared with the current method of only using statistical data and indexes from building regulations and standards, the approach in this thesis uses documents, interviews, questionnaires, field surveys and BEM methods to classify the current old residential stock and collect objective knowledge and information from RURB professionals and residents. It can provide more accurate and representative data to suit the local conditions and advantages of climate, retrofit measures and the opinions and preferences of residents.

Academic research: This thesis criticises the current problems of isolation, oversimplification, and lack of communication in RURB studies and advocates that researchers use the system perspective to understand and develop RURB.

Firstly, this thesis defined four different system players with equal emphasis on RURB development. The objective cognition of RURB was collected from all four system players to break the barriers of isolation. Secondly, this thesis used both a social survey and a field survey to provide the baseline scenario by collecting more realistic data from residents and the case study area. The purpose of these two methods is to reduce the oversimplification risk of using data from statistics and BEES only. Thirdly, this thesis emphasises the importance of residents' ROIDF. All six RURB scenarios were designed following the proposed three coherent and categorised concepts of a 'library of retrofit measures', 'global limit' and 'degree limits', which were indicated from the opinions and preferences obtained from the resident questionnaire survey.

7.5. Research limitations and directions for future research

Due to the researcher's limitations of time and budget, the social survey was carried out in the seven cities of the HSCW climate zone in China. The case study area selected in this study was also limited to one urban zone in the city of Chongqing and the total number of old residences surveyed was limited to 100 buildings. The classified reference buildings and retrofit scenario designs were hence only suitable for the conditions of one city and climate zone.

Future studies can be carried out based on the theoretical basis and methodology framework of this thesis to further enhance the RURB system perspective theory, RURB policymaking, and design and engineering in more diverse and detailed local conditions. The potential future research directions are listed as follows:

- Future studies could use the developed RURB system theory and research framework to investigate the retrofit potential of an urban area with other conditions to enhance the applicability of the statement in this thesis, including different climates, local economic levels, local policy, price of retrofit measures, energy price, occupant behaviours and residences with other old degrees.
- Future studies could conduct larger-scale field surveys of the selected urban area with more old residential buildings involved to produce a more detailed classification of reference buildings representing current old residences.
- Future studies could use the global limit and degree limit concepts from RURB system theory to proceed with a local social survey to collect more diverse data such as retrofit demands, cost allowances and preferences from RURB

professionals and residents (as retrofit ROIDF in SPA) in other case study areas to establish different, or more detailed, sub-scenarios based on the RSR, GDR and CR models identified in this research.

- For cities or countries with completely different styles of RURB policymaking and engineering to those in this case study, the RURB system may not be structured to include the same four groups of people. For example, some countries may currently have no governmental involvement in RURB development, hence the policymakers are no longer one of the RURB system players and the GDR model does not exist. Future studies may use the generalisability of the theory stream and methodology framework to identify their RURB system definition and to structure a unique RURB system cognition and interactions under specific national conditions.

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Appendix

Appendix A: Interview questions design

Table A: Interview questions design		
No.	Prompts	Keyword
Introduction		
1	Could you please briefly introduce yourself, about your educational background, your work experience, and your current role of organisation? Since when, and how long you have been working relevant to building retrofit?	Background
Policy related questions		
2	Could you please introduce the current policy system of RURB in China? - what is the procedure of design and implementation steps?	Policy system
3	How the effectiveness of current policy of RURB? The achievements? What are the problems in current RURB policy? (Implementing, index design, etc.)	Current policy
4	What are the challenges in the design process of RURB policy? What are possible improvements for future RURB policy design?	Future design
5	How are the current financial supports given by the national and local governments for RURB? What is the ideal future pattern to deal with financial problems for RURB?	Financial
Design & Engineering & Research questions		
6	What do you think about performance between new buildings and retrofitted buildings? How the performance index should be for ideal building retrofit design?	New and retrofitted
7	What is the engineering procedure of top-down government driven RURB? What is the engineering procedure of individual resident driven RURB?	Procedure, driven force
8	What is the most effective way for RURB? Alternatively, how to increase the RURB efficiency as much as possible in other ways?	Effectiveness
9	Are there any important, unique local characteristics should be considered during RURB design and engineering? (Including climate, cultural, economy, local citizens' behaviours, building material, etc.)	Local
Social and motivation questions		
10	What do you think are difficulties prevent residents to retrofit their home? (Cost, time, trouble, noise, availability of living place, material, etc.) What conditions may significantly increase the residents' desire of refurbishment?	Desire of retrofit
11	Ask yourself for example, have you recently considered retrofit your home? if yes, which aspects you are going to retrofit? If no, why? What do you think about how government or society should motivate you/other residents and let them start to retrofit their home?	Role substitution to residents
12	Do you think increase living comfort level while retrofit old residential buildings will cause trouble for energy conservation? As a policymaker/designer, for comfort and energy, which is more important? or how to balance?	Conflict: comfort and energy

Appendix B: Questionnaire questions design

Table B Questionnaire questions design

No.	Question	Selection	Keyword
Fundamental information			
1	How many areas are your major home?	< 40 m2 41~80 m2 81~120 m2 121~160 m2 > 160 m2	Area
2	How many people are living in your major home?	1 2 3 4 > 5	Occupant
3	Which building type is more relevant to your major home?	Bungalow Conventional Apartment Tower Detached House	Type
4	How long have you ever lived in this home?	< 1 year 1~3 years 4~6 years 7~9 years > 10 years	Lived time
5	Do you know the built age of your major home building?	Before 1980 1980~1995 1996~2010 2011~2015 After 2016 Don’t know	Built age
6	How long between now and last time of comprehensive refurbishment of your current major home?	< 1 year 1~3 years 4~6 years 7~9 years > 10 years Never Don’t know	Last retrofit
Thermal comfort			
7	Which choice is the most suitable to describe your thermal comfort feeling in summer, for your current home, if you do NOT switch on air-conditioning (AC)?	Very comfortable Comfortable Normal Uncomfortable Very uncomfortable	Summer
8	Which choice is the most suitable to describe your thermal comfort feeling in winter, for your current home, if you do NOT have any heating devices on?	Very comfortable Comfortable Normal Uncomfortable Very uncomfortable	Winter

9	Which type of heating devices you wish to introduce for summer cooling during retrofit, if there is no cooling device?	Fans Split air-conditioner Central system None	Wanted cooling device
10	Which type of heating devices you wish to introduce for winter heating during retrofit, if there is no heating device?	Hot water radiator Air conditioners with heating function Electricity heater Electricity blanket Radiating floor heating None	Wanted heating device
Energy			
11	What is your general feeling about your current electricity bill for summer cooling (air-conditioning, fans, etc.) in your home?	Too expensive Expensive, could be lower Acceptable Low I don't have these devices Don't know	Summer cooling bill
12	What is your feeling about your current energy bill for winter heating (air-conditioning, electronic blanket, radiant floor heating, etc.) in your home?	Too expensive Expensive, could be lower Acceptable Low I don't have these devices Don't know	Winter heating bill
13	Will you replace your old heating and cooling equipment with new one because of energy conservation purposes?	Yes, if I feel it is necessary Yes, but only after current devices are broken Maybe No	Efficiency
14	What factors are your most concern during HVAC equipment update? (Choose two)	Price Energy efficiency Looks and design Easy to install Long lifetime	Device
15	Will you increase the frequency of HVAC equipment usage after retrofit? (even it will increase energy bill)	Yes Maybe No	Higher bill
16	Do you want to retrofit your building façade to significantly reduce usage of cooling and heating devices to reduce the electricity bill for cooling and heating, will you consider about retrofit it yourself?	Yes Maybe No	Façade
Cost			
17	Do you think the cost issue is the biggest problem to prevent you from retrofit you home?	Yes Partly No	Feeling of cost
18	If you are going to retrofit your home (paid by yourself), with comprehensive refurbishment (means your home will be temporally unavailable to live), what will you retrofit/upgrade?	Wall Window Door Floor Roof Heating system Cooling system	Self-paid major retrofit

		Shading system Mechanical ventilation	
19	If you are going to retrofit your home with minor refurbishment (cause no trouble for living availability), what will you retrofit/upgrade?	Window Door Heating system Cooling system Shading system Mechanical ventilation	Self-paid minor retrofit
20	If government want to provide professional or financial supports to help you retrofit your home, which ways do you think are helpful?	Government-driven external wall retrofit programme Discount or subsidy of energy-efficient equipment Step energy tariff Government provides trustworthy retrofit teams Professional home retrofit companies with governmental pledge	Support from others
21	What components do you think are very costly when you are considering retrofit your home?	Purchase better equipment Purchase new furniture Purchase new appliance Labour cost of retrofit Materials of walls, roof, floor Windows, doors Extra living cost due to temporally move out	Highest cost
22	If you plan to have a comprehensive refurbishment of your major home, how much you think you are affordable to pay and achieve the best retrofitted result?	< 50,000 yuan 50,000 ~ 100,000 yuan 100,000 ~ 200,000 yuan 200,000 ~ 500,000 yuan 500,000 ~ 1,000,000 yuan > 1,000,000 yuan	Allowance of cost
Time			
23	Do you think the time-consuming issue is the biggest problem to prevent you from retrofit you home?	Yes, Partly No	Time cost
24	If you are going to retrofit your home with comprehensive refurbishment (this means your home will be temporally unavailable to live), how long would you think is maximum you can tolerate?	< 1 week 1~3 week 1~2 month 2~3 month > 3 months	Allowance of time
25	Do you want to retrofit your home within 3 years?	Yes No Not sure	Current desire
Desire of upgrade			
26	Do you want to have a comprehensive refurbishment, or minor retrofit?	Comprehensive Minor	Large or small

		Both	
27	Will you find construction team yourself to retrofit your external walls and add insulation to increase indoor thermal comfort and reduce energy bill?	Yes No Not sure	Façade
28	Do you want to retrofit your windows and doors to reduce thermal comfort, air infiltration, and noise issue?	Yes No Not sure	Window and doors
29	Do you want to upgrade your summer cooling devices with more energy efficient equipment during comprehensive retrofit?	Yes No Not sure	C/H device
30	If government or local real estate help to retrofit the external façade, shading etc. of your current home to increase thermal performance and reduce your energy bill, but there will be noise and troubles due to construction, will you be happy and cooperative?	Will cooperate Refuse to cooperate Not sure	Cooperate
Knowledge of retrofit			
31	Do you have the right or influence to making decision of retrofit?	Yes No Not sure	Right to decide
32	Do you have the knowledge of indoor design, retrofit, HVAC system, or built environment?	Know common sense Know professional knowledge No, but have some experience of fitting up None	Knowledge
33	Do you have experience in RURB policymaking or design?	Yes No	Experience
34	Overall, which results from the choice are relevant to your considerations, if you are going to retrofit your home?	Reduced energy bill Better indoor thermal comfort for heating and cooling Cleaner indoor ventilation More modern equipment and electrical appliance Clean, beautiful, and comfortable indoor environment Sustainability and environmental-friendly Reduced noise and air infiltration	Overall desire

Appendix C: National standards of building energy in China

Development of issued national building standards.

Code	Standard Focus	Year	Coved Building Type	Climate Zone*
TJ 19-75	HVAC design	1975	Industrial	National
GBJ 19-87	HVAC design	1987	All	National
JGJ 37-87	Architectural design	1987	Civil	National
GB 50176-93	Thermal design code	1993	Civil	National
GB 50189-93	Energy conservation design	1993	Hotel	National
GB 50096-1999	Architectural design	1999	Residential	National
JGJ/T 129-2000	Energy conservation retrofitting	2000	Residential	National
JGJ 134-2001	Energy conservation design	2001	Residential	HSCW
GB 50019-2003	HVAC design	2003	All	National
GB 50189-2005	Energy conservation design (2nd edition)	2005	Public	National
GB 50352-2005	Architectural design	2005	Civil	National
GB 50368-2005	Architectural design	2005	Residential	National
GB/T 50378-2006	Green building assessment	2006	Civil	National
JGJ/T 132-2009	Energy efficiency test	2009	Residential	National
JGJ 176-2009	Energy conservation retrofitting	2009	Public	National
JGJT 177-2009	Energy efficiency test	2009	Public	National
JGJ 134-2010	Energy conservation design	2010	Residential	HSCW
JGJ/T 229-2010	Green building design	2010	Civil	National
GB 50096-2011	Architectural design	2011	Residential	National
GB/T 50668-2011	Energy conservation building assessment	2011	Civil	National
GB 50736-2012	HVAC design	2012	Civil	National
JGJ/T 129-2012	Energy conservation retrofitting (2nd edition)	2012	Residential	National
GB/T 50824-2013	Energy conservation design	2013	Rural residential	National
GB/T 50378-2014	Green building assessment (2nd edition)	2014	Civil	National
CSUS/GBC 05-2014	Green building testing	2014	Civil	National
GB 50189-2015	Energy conservation design (3nd edition)	2015	Public	National
GB 50176-2016	Thermal design code	2016	Civil	National
GB/T 51161-2016	Energy consumption control	2016	Civil	National
JGJ/T 425-2017	Green retrofitting of existing community	2017	Civil	National
JGJ 26-2018	Energy efficiency design	2018	Residential	SC & C
GB/T 50378-2019	Green building	2019	Civil	National
GB/T 51350-2019	Nearly-Zero Energy building	2019	Civil	National
GB 21455-2019	Minimum allowable values of the energy efficiency and energy efficiency grades for room air	2019	-	National

Development of issued national building standards.

Code	Standard Focus	Year	Coved Building Type	Climate Zone*
	conditioners			
GB/T 8484-2020	Building exterior doors and windows	2020	Civil	National
GB/T 2589-2020	Calculation of energy consumption	2020	-	National
GB 55022-2021	Maintenance and renovation	2021	Civil	National

*Standards in grey colour are specific building energy conservation standards