A Model for Developing Retrofitting Strategies for Office Buildings

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Certificate of Original Authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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List of Abbreviations

ABCB	Australia Building Codes Board
AC	Alternating current
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ASGB	Assessment Standard of Green Building
ASHRAE	American Society of Heating Refrigerating and Air-Conditioning Engineers
BCR	Benefit/cost ratio
BEES	Building for Environmental and Economic Sustainability
BEEX	Building Energy Exchange
BIM	Building Information Modelling
BMCS	Building management control system
BMS	Building management system
BREEAM	Building Research Establishment Environmental Assessment Method
BSI	British Standards Institution
CBA	Cost benefit analysis
CFD	Computation fluid dynamics
CIB	International Council for Research and Innovation in Building and Construction
DC	Direct current
EAC	Equivalent annual cost
EC	Embodied carbon
ECBA	Environmental cost benefit analysis
EE	Embodied energy
eGRID	Emission & Generation Resource Integrated Database
ELCA	Environmental life cycle assessment
ELCC	Environmental life cycle costing

EPA	Environmental Protection Authority (U.S.)
EPD	Environmental product declarations
FU	Functional unit
GBRS	Green building rating system
GHG	Greenhouse gases
GP	Goal programming
HMD	Head-mounted display
HVAC	Heating, ventilation and air conditioning
I-O	Input-Output
ICE	Inventory of Carbon and Energy
IEA	International Energy Agency
IEQ	Indoor environmental quality
IESNA	Illuminating Engineering Society of North America
IRR	Internal rate of return
IVS	Immersive virtual simulation
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
LDPE	Low density polyethylene
LEED	Leadership in Energy and Environmental Design
MADM	Multi-attribute decision making
MCDM	Multi-criteria decision making
MLOP	Multiple linear objective programming
MNLOP	Multiple nonlinear objective programming
MODM	Multi-objective decision making

MOHURD	Ministry of Housing and Urban-Rural Development of the People’s Republic of China
MRL	Machine-room-less technology
NCC	National Construction Code
NIST	National Institute of Standards and Technology (US)
NPV	Net present value
OAT	One-At-a-Time
PBP	Payback period
PMV	Predicted mean vote
PP	Semi-crystalline polypropylene
PRPs	Performance reference points
PV	Photovoltaic
RSP	Reference study period
SDSN	Sustainable Development Solutions Network
SETAC	Society of Environmental Toxicology and Chemistry
S-LCA	Social life cycle assessment
SLCA	Social cost benefit analysis
SHGC	Solar heat gain coefficient
SOTNBS	Survey Office of The National Bureau of Statistics in Zhejiang
TBL	Triple-bottom line
UN	United Nations
UNEP	United Nations Environment Programme
VAT	Value Added Tax
VAV	Variable air volume
WCED	World Commission on Environment and Development
WLC	Weighted linear combination
WWR	Window/wall ratio
ZPBS	Zhejiang Provincial Bureau of Statistics

Abstract

A considerable amount of material, water, energy and other natural resources are invested in the building sector. The poor performance in energy efficiency of most existing buildings and the relatively low rate of new and more efficient construction means that it will be a long time before new buildings with better performance can replace existing poor building stock. Compared to demolition and construction of new buildings, retrofitting of existing buildings may be a faster method to modernise the existing stock and mitigate unfavourable impacts on the natural environment from the building sector. However, most existing sustainability assessment methods and decision-making frameworks focus on the environmental and economic performance of buildings without much consideration of the social dimension. While retrofitting may be the best chance for existing buildings to achieve sustainability, it is necessary to consider all three sustainability dimensions when retrofitting existing buildings to achieve economic growth, protect the natural environment, and increase social wellbeing.

This study develops a model for deciding retrofitting strategies for office buildings to improve their sustainability performance. Different with most other existing decision-making models for retrofitting strategies which only consider the environmental and economic dimensions, the model developed in this study integrates all the environmental, economic and social dimensions into the decision-making process of retrofitting strategies. The retrofitting strategies developed by the model can maximise improvement of existing buildings in these three dimensions within project constraints and meet retrofitting goals at the same time. This is realised via a process from conceptualisation to operationalisation. First, a conceptual model for deciding retrofitting strategies for office buildings from a triple-bottom line perspective is developed based on literature review. Then, the conceptual model is converted to an operating model to suit local situations for sustainable retrofitting. A survey and focus group discussions are conducted to collect opinions about locally suitable retrofitting activities and assessment criteria from professionals in the construction and property management sectors as well as the key stakeholders of retrofitting. Finally, a case study is conducted in which the operating model is used to develop retrofitting strategies for the case building. With suitable potential retrofitting strategies developed for the case building, the validity of the conceptual model is verified. Meanwhile, the case study illustrates the process of quantifying and using the conceptual model to develop retrofitting strategies for an office building.

Chapter 1. Introduction

1.1. Introduction

Previous studies have indicated that building-related activities pose a serious threat to the natural environment, and most of the negative impacts are from the operation phase of buildings. Therefore, improving the sustainability performance of existing buildings is crucial to achieve sustainable development for the whole of society. This study aims to develop a model for deciding retrofitting strategies for office buildings using the triple-bottom line approach. The retrofitting strategies developed by the model are able to maximise the improvement of the environmental, economic and social dimensions within project constraints. Therefore, it is expected that the developed model can help improve the overall sustainability performance of the whole building sector. This chapter discusses the general research background, research significance, research gaps, research questions, aim and objectives, methodology, and thesis structure to provide a brief introduction to the whole research.

1.2. Research background

Existing buildings cannot be regarded only as a space for human activities. They are also a significant consumer of energy and resources while generating greenhouse gases (GHG) and waste. In the past decades, the rapid development of the building industry has caused many problems including the depletion of resources for construction and global warming by the emission of greenhouse gases from the operation and maintenance of existing buildings (Ardente et al. 2011; Chau, Tse & Chung 2010). Moreover, the poor performance of most existing buildings and the relatively low rate of new construction mean there is a long period before new buildings with better performance can replace existing poor building stock (Wilkinson 2012). Therefore, how to alleviate the unfavourable effects of existing buildings while not interrupting the services they provide has become a significant issue for all communities.

Existing buildings are potentially important in solving environmental problems because most of them have low efficiency in energy and resource use (Asadi et al. 2014; Che et al. 2019; Heo, Choudhary & Augenbroe 2012). Considerable quantities of materials, energy, water and other natural resources are invested in the building sector annually with much waste and greenhouse gas output (Mikulić, Bakarić & Slijepčević 2016). Small and medium-sized commercial buildings in developed nations represent around 50% of energy consumed by all types of buildings (Juan, Gao & Wang 2010; Liang et al. 2018). Office buildings in particular are one of the largest energy consumers and greenhouse gas emitters (Krstić-Furundžić, Vujošević & Petrovski 2019) because the complex building systems of office buildings, including heating, ventilation and air conditioning (HVAC), lighting, and security systems, require extensive energy and natural resources to maintain their normal function (Luo et al. 2018). Moreover, different types of system failures may occur in office building services, increasing the energy used (Juan, Gao & Wang 2010). As for emissions, the greenhouse gases released from existing commercial buildings are 41% of total greenhouse gas emissions by buildings globally (Chidiac et al. 2011; Hong et al. 2019), and approximately 70% to 90% of emissions are from the operation stage (Toosi et al. 2020; Wu et al. 2014; Yuan, Nian & Su 2019). The data indicates that the environmental performance of existing buildings may not meet the demand for sustainability and is a serious threat to the natural environment.

Throughout the whole life span of buildings there are several stages, including design, construction, operation and end-of-life. Energy demands and adverse environmental impacts from buildings vary in different phases, but most impacts are concentrated in the operation stage (Ardente et al. 2011; Toosi et al. 2020). As discussed above, the operation stage is responsible for the majority of energy consumption and greenhouse gas emissions during a building's whole life span. While embodied energy becomes increasingly significant due to the continuous development of technology, reductions in embodied energy only occur in new buildings with advanced energy efficiency equipment and management strategies (Simonen 2014). For this reason, improving existing buildings' environmental performance is an opportunity to significantly reduce energy impacts.

Apart from environmental performance, the economic performance of existing buildings is also not ideal. Due to the large amount of energy consumed in the operation stage and high and increasing energy prices, the operation stage is regarded as the most critical stage due to its huge economic impacts during the whole life of buildings (Oregi, Hernandez & Hernandez 2017). Past studies have estimated that if a building's life is 50 years the operation and maintenance costs account for approximately 75%–80% of the total costs in a building's life cycle (Hauashdh, Jailani & Rahman 2022).

In addition, indoor environmental quality is also related to the economic performance of existing office buildings. Sound indoor environmental quality of existing office buildings in the UK can contribute to up to 20% improvement of occupant productivity, which is equivalent to £135 billion per year (Horr et al. 2016). In contrast, the poor indoor environmental quality of existing office buildings reduces maximum possible rents, and increases utility bills, resulting in a long payback period for construction investment (Oregi, Hernandez & Hernandez 2017). Due to the growing recognition of the importance of healthy living and work environments as well as the higher productivity benefits, expenditure on improving indoor environmental quality in the US, especially for commercial buildings, has been increasing, and is estimated at hundreds of billions of dollars annually (Kats 2003; Kibert 2016).

Sustainability has been regarded as a significant marketing device by large companies because it can be used to describe the production methods of economic activities, and also to improve the quality of consumption and attributes of capital investment (Eichholtz, Kok & Quigley 2013). The environmental benefits of improving sustainability also contribute to economic growth for individuals and the public (Cetiner & Edis 2014; Mikulić, Bakarić & Slijepčević 2016). In contrast, poor environmental performance brings a weaker financial return. With higher energy prices expected in the future, the investment opportunities for energy-efficient retrofitting are likely to increase and are expected to become one of the main driving forces for owners to retrofit existing buildings (Amstalden et al. 2007; Pombo, Rivela & Neila 2016).

Regarding the social dimension, the social impacts of the building industry do not receive much consideration compared to environmental and economic aspects (Santos et al. 2017). However, the productivity of employees and corporate culture, two aspects under the social dimension, are affected by building performance (Zuo & Zhao 2014). For a long time, researchers have not had complete agreement on what social elements should be included in the context of sustainable buildings. Watson et al. (2016) believed that the social context can be expressed as building user group dynamics, which is an integration of institutional norms, culture and management. Wilkinson and Remøy (2017) and Parida et al. (2021) identified social contexts for office buildings, which are work-related flow, comfort, wellbeing, and job satisfaction of occupants. Liu and Qian (2019) stated that the social context of a building project is supposed to meet the diverse requirements of multiple stakeholders involved in the whole project process including construction teams, suppliers, end users, and local communities. Indeed, construction activities generate various social impacts on individuals, communities, and even the whole of society. The wide coverage and the intangible characteristics of the social context make the social dimension one of the most challenging when aiming for sustainable buildings overall (Dendena & Corsi 2015; Zuo & Zhao 2014).

As an indirect way to preserve the cultural and societal assets that have been embodied in existing buildings, building retrofitting should not be carried out without social impact assessment (Jagarajan et al. 2017). The sound practice of social performance assessment should not only achieve effective engagement of different stakeholders, and increase understanding of change and capacities to respond to change, but also help to enhance the lives of vulnerable and disadvantaged people (Esteves, Franks & Vanclay 2012). Due to the increasing extent of retrofitting construction all over the world, social impact assessment for existing buildings is becoming more urgent, and more comprehensive social assessment models are required.

To solve the environmental, economic and social problems mentioned above, two solutions can be adopted: demolition or retrofitting. Buildings are a long-lasting product that need regular maintenance and renewal, but still cannot avoid becoming obsolete or redundant due to the continual change in demand and regulations. Eventually, obsolete buildings are demolished and new buildings are built complying with current standards and regulations, but the obsolescence stage can be delayed by retrofitting (Ongpenga et al. 2020; Solanki, Rastogi & Paul 2022). The reason for preferring to retrofit is that fewer resources and energy are required compared to demolition and new construction. Moreover, the embodied energy of existing buildings already exists. If buildings' performance can be enhanced by retrofitting, demolition and then new construction are a waste of both energy and time (Thomsen & Van der Flier 2011).

Considering the extensive number of existing office buildings around the world, the assessments for evaluating existing office buildings' performance and generating appropriate retrofitting strategies are crucial for sustainable building development. However, current assessment systems for existing office buildings rarely cover all of the three sustainable pillars: environmental, economic and social dimensions (Phillips et al. 2020). The (perceived) high initial cost is one of the main obstacles to sustainable construction (Aghimien, Aigbavboa & Thwala 2019; Gunduz & Almuajebh 2020). In fact, the problem is that those assessment frames do not take a long-term perspective and are not able to balance different stakeholders' benefits so that the short-term payback and the risk of concerns by stakeholders mean retrofitting is not attractive (Maltz, Bi & Bateman 2018).

Due to the complex process of building retrofitting, it is difficult to develop appropriate retrofitting strategies that can embrace all the environmental, economic and social dimensions from a long-term perspective. This study aims to contribute a solution to define methods of improving the sustainability performance of existing office buildings, reducing the pollution, increasing economic growth, and enriching the social value. The research reviews current assessment methods for environmental, economic and social impacts of construction and buildings. Existing retrofitting activities that can reduce environmental damage and increase economic benefits and social value are also examined and analysed. The collected data and analysed information are then used to develop a conceptual model for deciding retrofitting strategies, and a case study is conducted to verify the validity of the conceptual model and illustrate how to use the model to develop retrofitting strategies for an office building.

1.3. Research significance

There is no doubt that building retrofitting can make a significant difference in dealing with environmental problems, but environmental concerns should not be the only focus of sustainable retrofitting (Ardente et al. 2011; Chidiac et al. 2011). Most of the existing assessment frameworks for upgrading existing buildings concentrate on the environmental and/or economic dimensions, but the social dimension is rarely considered (Ball 1999; Fatourehchi & Zarghami 2020; Mickaityte et al. 2008; Yung & Chan 2012).

Indeed, social sustainability has been recognised as the most difficult element of sustainability due to the wide range covered and its "soft" characteristics (Watson et al. 2016). Therefore, researchers prefer to study this dimension on its own instead of integrating it with the other two pillars. As a result, using assessment tools to balance the environmental and economic performance is a common way to create a green built environment (Escrig-Olmedo et al. 2017; Fouche & Crawford 2017). However, retrofitting is the second, and probably the last, chance to pursue sustainability for existing buildings (Kohler et al. 2010). Therefore, the assessment process should include a broad context to account for all the life stages of a building's life cycle. The absence of the social dimension may hinder the understanding of the sustainability of buildings from a full life cycle perspective (Simonen 2014).

Numerous sustainable building assessment methods for new buildings have already been established and well developed due to the rapid growth of sustainable building development. However, it is still a great challenge to develop assessment models for existing buildings, especially for integrating the three sustainability dimensions into the assessment process (Andersen, Jensen & Ryberg 2021; Filippi & Sirombo 2015). This research aims to develop a model for deciding retrofitting strategies for office buildings. The developed model is able to address the environmental, economic and social issues of existing office buildings and balance the trade-offs between the three sustainability dimensions from a long-term perspective. In this way, the concerns and benefits of different stakeholders can be considered and balanced, so that the selected retrofitting strategy is more appropriate, and can increase interest in retrofitting buildings.

This study contributes to providing a new approach for assessing the value of existing office buildings and deciding suitable retrofitting decisions to reduce the environmental pollution, to increase financial return, and to enrich social value. Meanwhile, all stakeholders' awareness of sustainability can be improved through participating in the assessment process. Ultimately, the sustainable performance of the whole building industry can be improved.

1.4. Research gaps

Most effort has been paid to developing new buildings, and it is the reason why few assessment tools are available for building retrofitting. Currently, there are some assessment tools and regulations for assessing the performance of existing buildings, like the life cycle assessment (LCA) for assessing environmental impacts of buildings, the life cycle costing (LCC) tool for evaluating buildings' economic performance, and Europe Standard EN 16309 for assessing buildings' social performance (BSI 2014). However, these assessment strategies do not adequately provide data or guidance for sustainability improvement by only focusing on one dimension. Filippi and Sirombo (2015) stated that it is time to deeply examine the sustainability performance of existing buildings and facilities.

Three major research problems need to be solved through this research:

i) Current retrofitting assessment tools are ineffective and inefficient in dealing with sustainability issues due to their failure to integrate all the three sustainability dimensions by just focusing on the environmental and/or economic dimensions.
ii) To obtain a suitable retrofitting strategy, different decision-making support tools need to be integrated with assessment models. The variation from integrating different tools may generate different results for the same case.
iii) The process of retrofitting buildings is very complicated and various stakeholders may be involved at the same time, and the benefits and unfavourable impacts from retrofitting are generated at different stages of a building's whole life span. Therefore, how to balance benefits among different stakeholders, or maximise trade-offs between different sustainability dimensions, and evaluate the performance of existing buildings from a long-term perspective should be considered in an assessment framework.

Based on the identified research problems, this study aims to address the gaps by developing:

i) a conceptual model for deciding retrofitting strategies, which can integrate the environmental, economic and social dimensions of sustainability

ii) a way to maximise the trade-offs between the three sustainability dimensions from a long-term perspective.

1.5. Research questions

Based on the research problems and gaps discussed above, the research question is:

How can we develop retrofitting strategies that can effectively improve an office building's environmental, economic and social performance in a balanced manner?

To answer this research question, the following sub-questions are formulated:

i) How can the environmental, economic and social dimensions be considered in retrofitting?
ii) How can we use the resulting assessment outcomes of retrofitting activities to generate suitable retrofitting strategies?
iii) How can we balance the improvement on the three sustainability dimensions in a balanced manner?

Through a deeper understanding of building sustainability, the study can determine whether this approach can contribute to improving the sustainable performance of existing office buildings.

1.6. Research aim and objectives

This research aims to develop a model for developing retrofitting strategies for office buildings to improve their sustainability performance. To accomplish this research aim, specific objectives are:

i) To examine the current performance of existing office buildings in a triple-bottom line aspect that includes the environmental, economic and social dimensions
ii) To investigate existing assessment methods for building retrofitting
iii) To identify the process and significant criteria impacting building retrofitting on environmental, economic and social dimensions
iv) To identify the trade-offs between the three sustainability dimensions, which reflect the conflicts of interest among different stakeholders
v) To develop a conceptual model that can be used to develop retrofitting strategies based on the evaluation results of potential retrofitting activities
vi) To verify the conceptual model by converting it to an operating model and quantifying the operating model based on a case study.

1.7. Research methodology

There are two major theoretical perspectives in social science: positivism and interpretivism. In the positivism perspective, positivists seek facts or causes of social phenomena in an objective way avoiding the involvement of individual judgment (which is hard to achieve). In the interpretivism perspective, interpretivists or phenomenologists attempt to understand social phenomena based on personal knowledge, experience and viewpoint. These two theoretical perspectives take different kinds of problems and seek different types of answers, so two different methodologies which are common in social science are developed: quantitative methodology and qualitative methodology (Cresswell 2012; Fellows & Liu 2015; Taylor, Bogdan & DeVault 2015). Quantitative methodology puts considerable trust in numerical data; in contrast, qualitative methodology attempts to use words and observations to describe reality (Amaratunga et al. 2002). Even though there is a clear difference between these two methodologies, qualitative and quantitative methods are not mutually exclusive, and qualitative methods can still be used by positivists to address their research problems (Hughes 2012; Taylor, Bogdan & DeVault 2015).

This study takes the positivism perspective to confirm that sustainable retrofitting can effectively improve existing buildings' environmental, economic and social performance. To solve research questions effectively and efficiently, the mixed method approach is adopted to collect both quantitative and qualitative data. Based on the above discussion, a research proposition can be identified that it is possible to improve sustainability while potentially allowing economic growth and improved social wellbeing by retrofitting existing buildings using the triple-bottom line approach. To test this research proposition, two main tasks need to be achieved in this study:

Task 1: Examine the interaction between existing office buildings and all sustainability dimensions. Understand reasons for sustainable retrofitting, existing assessment methods for building retrofitting, and other relevant background knowledge by reviewing the literature. Based on the knowledge and information from the literature review, develop a conceptual model for deciding retrofitting strategies for office buildings.

Task 2: Verify the conceptual model and illustrate the process of using the model to develop retrofitting strategies for an office building through a case study.

To accomplish the first task, related literature, including journal papers, books, reports and research studies, is reviewed. The topics of reviewed literature are not limited to sustainable buildings, but also theory and practice about how to achieve group consensus, normalisation methods, weighting methods, and so on. The literature review failed to locate any assessment system that enables the user to evaluate the environmental, economic and social dimensions for existing office buildings while determining suitable retrofitting strategies. Based on the literature review, a conceptual model for developing retrofitting strategies for office buildings was developed by using a triple-bottom line approach.

The second task is to verify the developed model and illustrate how to use the model to develop retrofitting strategies for an office building via a case study. The conceptual model is intended to be general, and it needs to be adapted to suit the local situation before applying it to an actual retrofitting project. A case study in China is conducted to illustrate the detailed process from converting the conceptual model to an operating model, and then using the operating model to develop retrofitting strategies for the case building. There are approximately 60 billion m^2 of floor space in existing buildings in China. Most of these existing buildings have poor operations and energy inefficiency, resulting in high energy consumption and greenhouse gas emissions (Liu, Tan & Li 2020). Based on the study by Guo et al. (2022), operations energy by existing buildings in China accounts for 22% of total national domestic energy consumption, with non-residential buildings being the largest contributor. The Chinese government is also promoting sustainable retrofitting by launching various policies, which makes China a big market for retrofitting (Liu, Tan & Li 2020). Therefore, China is a suitable place to conduct the case study. Meanwhile, with diverse climate conditions in China, it is also a good opportunity to demonstrate the flexibility of the developed model.

In the case study, a two-stage data collection strategy is adopted to collect opinions about suitable retrofitting activities and assessment criteria for local retrofitting from the broad to the specific. First, a survey is conducted with professionals and key stakeholders in retrofitting in both northern and southern China to collect broad opinions. Following the survey, focus group discussions with local professionals and key stakeholders of retrofitting are organised to consolidate the results of the survey and further modify the retrofitting activities and assessment criteria to be suitable for local use. After finalising retrofitting activities and assessment criteria, the operating model is then implemented to develop retrofitting strategies for the case building, to maximise the improvement in the environmental, economic and social dimensions while meeting the retrofitting goals within project constraints.

The process from conceptualisation to operationalisation can be regarded as a logically and methodologically correct framework for the work done and to be done in the future. By copying the process, the conceptual model can be adapted according to the specific situation of each retrofitting project and be used to develop retrofitting strategies.

1.8. Thesis structure

The structure of the thesis is represented in Table 1.1. The outline of each chapter is described as follows.

Chapter 1. Introduction

This chapter introduces the background information about this research. By discussing the research significance, research gaps, research problems, and research aim and objectives, this chapter introduces the reasons for undertaking this research – why a model for deciding retrofitting strategies needs to be developed. It also describes the research methodology including how to develop the conceptual model, and how to verify and illustrate the implementation of the developed model.

Chapter 2. Sustainable development of construction

This chapter reviews sustainable development of construction. First, based on existing studies about sustainable development and sustainable construction, the definition of sustainable retrofitting is given. It is a process of realising the reduction of cost of operating a building and increasing people's wellbeing in ways that reduce the deterioration of natural systems. Due to the diverse aspects, the context of sustainable construction can be categorised into different dimensions. The three-dimension model complying with the context of the triple-bottom line – the environmental, economic and social – is widely adopted to assess the sustainability performance of construction. This chapter also discusses the challenges facing sustainable construction that need to be overcome through this study to achieve sustainable retrofitting.

Chapter 3. Sustainable retrofitting of office buildings

This chapter reviews existing studies about sustainable retrofitting. First, the current environmental, economic and social performance of existing office buildings around the world is discussed. Due to the increasing demand for indoor thermal comfort and stricter regulations about building energy consumption and carbon emissions, the environmental and economic performance of existing office buildings is worse than for new buildings. The social dimension does not attract the same attention as the environmental and economic dimensions, leading to a lack of mature social assessment methods. To improve the sustainability performance of existing buildings, two solutions are retrofitting existing buildings or demolishing and replacing them with new buildings. This chapter discusses reasons why retrofitting is preferred over demolition. Retrofitting can deliver a faster improvement of sustainability performance, and also saves the embodied energy and embodied carbon emissions that already exist in existing buildings. Common activities for retrofitting office buildings are summarised by their potential improvement and interruption to building tenants.

Chapter 4. Sustainability assessment methods for buildings

This chapter reviews existing literature about assessment methods of sustainable buildings. To assess the environmental impacts of buildings, life cycle assessment (LCA) is the most popular method of assessing buildings’ environmental impacts from a life cycle perspective. Moreover, different green building rating systems, such as the Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Assessment Method (BREAM), can be used to rate the sustainability level of buildings. To assess buildings’ economic impacts, life cycle costing (LCC) and cost benefit analysis (CBA) are two popular methods. To assess buildings’ social impacts, social cost benefit analysis (SCBA) and social life cycle assessment (SLCA) are two common methods to quantify the social impacts of buildings. These are assessment methods for only one of the three sustainability dimensions.

Often the environmental and economic impact assessment methods are combined as a two-dimensional assessment model to assess a building’s sustainability performance. Life cycle sustainability assessment (LCSA) is an assessment method consisting of the life cycle assessments in all three sustainability dimensions – LCA, environmental life cycle costing (ELCC), and SLCA. Multi-criteria decision making is also discussed in this chapter due to its ability to integrate the three sustainability dimensions into sustainability performance assessment and generate one overall assessment result to assist in decision making of retrofitting strategies. This chapter discusses benefits and limitations of the assessment methods and justifies why multi-objective decision making, which is a branch of multi-criteria decision making, is selected in this study to develop a conceptual model for deciding retrofitting strategies.

Chapter 5. Research methodology

The chapter discusses the research methodology and research design to explain how this study is conducted. This research aims to develop a model for deciding retrofitting strategies for office buildings and uses a case study to quantify the model. This aim is achieved via a process from conceptualisation to operationalisation. First, a conceptual model is developed based on information and knowledge from the literature review. Then, a case study is conducted to verify the validity of the conceptual model and illustrate how to use the conceptual model to develop retrofitting strategies. There are two parts in the case study. The first part converts the conceptual model to an operating model by modifying retrofitting activities and assessment criteria to suit the local situation. To accomplish the conversion, a survey and three focus group discussions are conducted to collect opinions from local professionals and key stakeholders of retrofitting. The second part implements the operating model to develop retrofitting strategies for the case building. Based on detailed illustration, the process from conceptualisation to operationalisation can be regarded as a logically and methodologically correct framework for the work done and to be done in the future. By copying the process, the conceptual model can be adapted according to the specific situation of each retrofitting project and be used to develop retrofitting strategies.

Chapter 6. Development of a conceptual model for deciding retrofitting strategies for office buildings

This chapter develops a conceptual model for deciding retrofitting strategies for office buildings by using the triple-bottom line approach. The decision-making process in the conceptual model is designed based on multi-objective decision making, which can deal with multiple conflicting objectives. By following the steps in the conceptual model, the developed retrofitting strategies may meet all the identified retrofitting goals and maximise the improvement in the environmental, economic and social dimensions within project constraints.

Chapter 7. Case study – Data collection

To verify the validity and illustrate how to use the conceptual model to develop retrofitting strategies for an office building, a case study of retrofitting an office building in China is conducted. This chapter presents the first part of the case study – data collection to convert the conceptual model to an operating model to deal with locational variation. A two-stage data collection strategy is adopted to collect data from the broad to the specific. Stage one gathers broad opinions about suitable retrofitting strategies and assessment criteria for retrofitting in China. A survey, which can gather quantitative data in a relatively short time, is conducted with professionals and key stakeholders of retrofitting in northern and southern China. To consolidate the results of the survey and further modify the model to be suitable for the case building and other buildings in China, three focus group discussions are conducted with local professionals and key stakeholders. The participants of focus group discussions are also invited to determine weights for the three sustainability dimensions and the assessment criteria for each dimension using the Analytic Hierarchy Process (AHP) method.

Chapter 8. Case study – Quantifying the operating model

With finalised retrofitting activities and assessment criteria, this chapter describes how to use the operating model to develop retrofitting strategies for the case building. By following the steps in the conceptual model, five retrofitting strategies are developed for the case building. The building owners can choose the strategy that can best satisfy their demands as the final retrofitting strategy. The results of the case study are also compared with the Chinese national standard, Assessment Standard for Green Retrofitting of Existing Building (GB/T 51141-2015) (MOHURD 2015) to confirm the effectiveness of the developed model. This chapter discusses and analyses the outcome of the case study to deeply explore how the developed model can improve the sustainability performance of existing buildings.

Chapter 9. Summary and conclusion

This chapter summarises the research process and presents how the research questions are answered, how the research problems are addressed, and how the research aim is reached. It also discusses the general contribution and limitation of this research, and also offers recommendations for future research.

Table 1.1. Thesis structure

Chapter	Title	Content	Achieved research objective or solved research question
1	Introduction	Introduces research background, research question, research problem, research aim and objectives, and identifies research gap.	
2	Sustainable development of construction	Discusses necessity and limitation of sustainable construction.	Research objective (i), (iv)
3	Sustainable retrofitting of office buildings	Reviews previous literature about sustainable retrofitting regarding reasons for retrofitting, obstacles in conducting retrofitting, and common retrofitting activities for office buildings.	Research objective (i), (iii)
4	Sustainability assessment methods of buildings	Reviews existing methods of assessing sustainability of constructions and building in the environmental, economic and social dimensions, individually or jointly.	Research objective (ii), (iv) Research question (i), (iii)
5	Research methodology	Introduces the methodology and data collection methods used in the research and discusses the benefits and limits of each adopted method. Presents the research design on the research methodology and data collection methods to reach the identified research aim.	
6	Development of a conceptual model for deciding retrofitting strategies for office buildings	Uses the information and knowledge from the literature review to develop a conceptual model to decide retrofitting strategies for office buildings.	Research objective (v) Research question (ii), (iii)
7	Case study – Data collection	Conducts survey and focus group discussions to collect opinions about suitable retrofitting activities and assessment criteria for the local retrofitting of the case building.	Research objective (vi)
8	Case study – Quantifying the operating model	Implements the operating model to develop retrofitting strategies for the case building.	Research objective (vi)
9	Summary and conclusion	Summarises main content of the research, discusses the results of the research, and discusses the outcome of the research.	

1.9. Summary

Improving the sustainable performance of existing buildings is a challenge for sustainable development, but it can also be an opportunity to make a difference. This research develops a model for deciding retrofitting strategies for office buildings by considering impacts on the three sustainability dimensions – environmental, economic and social dimensions. To build this model, a substantial literature review about sustainable development, sustainable retrofitting and sustainability assessment methods is undertaken. A case study is then conducted to verify the conceptual model and illustrate the detailed process of converting the conceptual model to an operating model and using the operating model to develop retrofitting strategies for the case building.

The outcome of this research is that the developed model can demonstrate the ability to assess multiple facets of sustainability and also to decide suitable retrofitting strategies for office buildings. This research is expected to promote deeper and broader study on building retrofitting by providing a new perspective of sustainability assessment, so that the overall sustainability level of buildings can be improved.

Chapter 2. Sustainable development of construction

2.1. Introduction

This study aims to develop a model for deciding retrofitting strategies for office buildings to improve their sustainability performance. To achieve the research aim, it is essential to investigate the background and tendency of sustainable development, especially in the construction and property sector. In addition, related studies about sustainable retrofitting such as the performance of existing office buildings, common retrofitting activities, assessment methods of sustainable development, and common decision-making frameworks should be reviewed to support the model development. Therefore, a literature review is conducted in Chapter 2 to Chapter 4 to illustrate related studies about sustainable retrofitting. First, existing studies about sustainable development and the triple-bottom line of construction are reviewed in this chapter. Then, the performance of existing office buildings and sustainable retrofitting application is investigated in Chapter 3. In Chapter 4, existing assessment methods and decision-making frameworks of sustainable development are reviewed. The literature review illustrates that it is possible to measure the level of complex changes in the level of sustainable development by adopting the specific view of sustainable development, suitable sustainability assessment methods, and a proper decision-making framework.

In this chapter, existing studies on the concept of sustainable development are reviewed first with analysis of its necessity and limitations. Then, studies about using the triple-bottom line approach to evaluate sustainability performance of construction are investigated. Some other significant aspects that should be considered in using triple-bottom line to achieve sustainable construction are also discussed.

2.2. Definition of sustainable development

The concepts of sustainability and sustainable development are becoming increasingly popular and are widely adopted to label the “green” traits of products, projects and even behaviours. The concept of sustainability is traceable to the forest industry, describing that the speed of harvesting should never be faster than the rate of growth of new trees (Wiersum 1995). The most well-known and widely used definition is given in the Brundtland Report “Our common future" by the World Commission on Environment and Development (WCED) in 1987. In the report, the concept of sustainable development is proposed and defined that humanity should make development sustainable such that it can meet the current generation's needs without jeopardising future generations' ability to meet their own needs (Brundtland 1987). Brundtland (1987) emphasised that the natural environment is a finite resource that places certain limits on development, and humans have the responsibility of preserving and protecting it from depletion for their descendants. Moreover, Brundtland (1987) pointed out that the essence of sustainable development is to realise a harmonious process of change in resource exploitation, investment direction, technology development orientation, and institutional change so that both current and future potential for meeting human needs and aspirations can be improved.

The WCED started a new era of sustainable development, and since then, the concept of sustainable development has been widely disseminated and implemented in various fields (Conte 2018; Sadollah, Nasir & Geem 2020). In past decades, multiple authors have discussed the concept of sustainable development, which now has over 200 definitions (Santos et al. 2019). Sadollah, Nasir and Geem (2020) provided a summary of the concept and definition of sustainable development as shown in Table 2.1. The definition of sustainable development is influenced by how people understand it and why they need it, such as the type of problems they need to solve. Thus, Sadollah, Nasir and Geem (2020) stated that the concept of sustainable development is prone to favouritism and is subjective.

Table 2.1. A summary of concepts and definitions of sustainable development

Roots of sustainable development	Points of emphasis	Definition of sustainable development	Specific sustainable development emphasis
Ecological/carrying capacity	Maintenance of natural systems so that they can support human life and wellbeing	Carrying capacity	Optimum and maximum ability of Earth's systems to support human life and wellbeing
Resource/environment	Promoting economic growth only to the extent and in ways that do not cause deterioration of natural systems	Sustainable use of biological resources	Maximum sustainable yield from natural systems, such as forests and fisheries
Biosphere	Concern with the impacts of humans on the health of ecosystems and its ability to support human populations	Sustainable agriculture	Maintaining productivity of farming during and after disturbances such as floods and droughts
Critique of technology	Rejection of the notion that science and technology, by themselves, will protect and save the Earth	Sustainable energy	Renewable alternatives to fossil fuel reliance to produce heat energy
No growth-slow growth	Limit to the ability of the Earth to support the health and wellbeing of ever-growing populations	Sustainable society and economy	Maintaining human systems to support economic and human wellbeing
Ecodevelopment	Adapting business and economic development activities to realities of natural source and environmental limits	Sustainable economic and environmental development	Promoting economic growth only to the extent and in the ways that do not cause deterioration of natural systems

Source: Adapted from Sadollah, Nasir & Geem 2020

There is a need to point out the difference between sustainability and sustainable development. In most studies, the terms are used interchangeably, but there is a subtle difference between them. Conte (2018) believed that the word "sustainability" represents a level of concept while "sustainable development" is more about the operational level of development. Similarly, Sadollah, Nasir and Geem (2020) explained that sustainability is the capacity for long-term development, and sustainable development is a dynamic process of achieving or considering the development. In this study, sustainable development is adopted since the study is about a process of realising sustainability (performance improvement) of existing buildings via the retrofitting strategies determined by using the model developed in this study (see Chapter 6). The definitions of sustainable society and economy, and sustainable economic and environmental development from Table 2.1 are combined to define sustainable retrofitting for this study as a process of realising the reduction of cost of operating a building and increasing human wellbeing in ways that reduce deterioration of natural systems.

2.3. Significance of sustainable construction

The substantial consumption of energy and materials, the massive carbon emissions and the waste generation of the construction industry and the built environment make them the key areas in which to achieve sustainable development, thus contributing to the achievement of sustainable development for the whole of society (Amaral et al. 2020). Table 2.2 summarises energy and other resources consumed by buildings in different countries. Greenhouse gas emissions and waste generation from using and maintaining buildings also have harmful impacts on the natural environment. According to Table 2.2, about 30% to 50% of global energy consumption and 40% to 50% of greenhouse gas emissions are from the building sector. Around 30% of resource consumption, 40% of raw materials, and 12% to 25% of water consumption are also generated by the building sector, and it also generates about 25% to 40% of global waste.

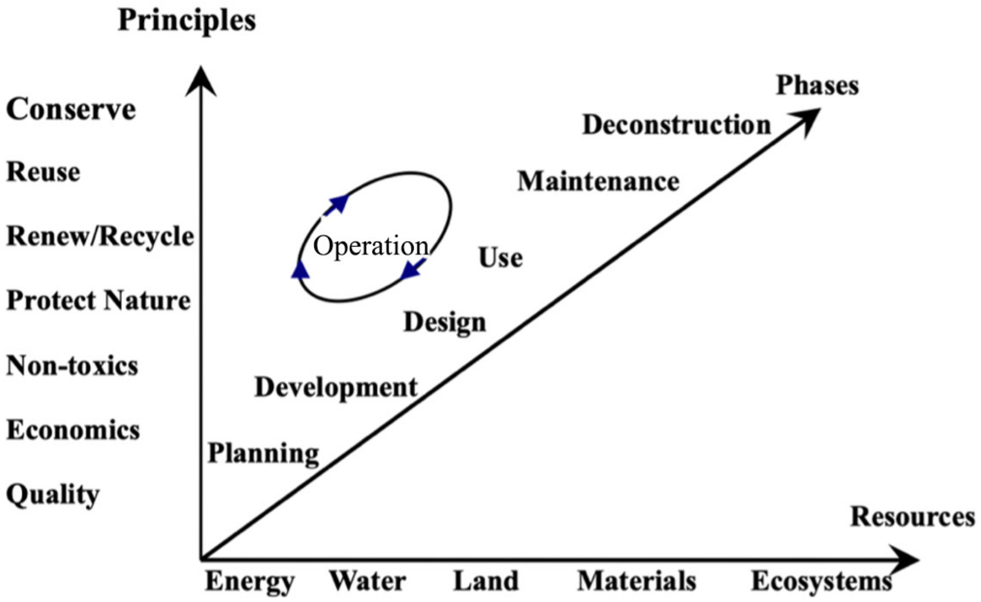
Table 2.2. Environmental pollution from the building sector

Consumption/ emissions	**Percentage of consumption/ emissions**	**Location**	**Source**
Energy consumption	40%~42%	EU	Kolokotsa et al. 2009; Ardente et al. 2011; Cedllura et al. 2013; Asadi et al. 2014; Wang, Xia & Zhang 2014; Mauro et al. 2015; Kylili, Fokaides & Jimenez 2016; Mikulic, Bakaric & Slijepcevic 2016; Oregi, Hernandez & Hernandez 2017; Baumhof et al. 2018
	≈40%	US	Azhar, Brown & Farooqui 2009; Frey et al. 2012; Heo, Choudhary & Augenbroe 2012; Liu, Meng & Tam 2015
	39%	UK	Heo, Choudhary & Augenbroe 2012
	50%~60%	China	Peng, Wang & Zhang 2014
	30%~50%	Global	Lippiatt 1999; Miller & Buys 2008; Kolokotsa et al. 2009; Motawa & Carter 2013; Wang, Xia & Zhang 2014; Zuo & Zhao 2014; Chau, Leung & Ng 2015; Mauro et al. 2015; Dwaikat & Ali 2016; Radziejowska & Orlowski 2016; Oregi, Hernandez & Hernandez 2017; Pomponi & Moncaster 2017; Baumhof et al. 2018; Amaral et al. 2020
Resource consumption	33%	Global	Langston et al. 2008; Dwaikat & Ali 2016
Raw material consumption	35%	EU	Cellura et al. 2013
	40%	Global	Ardente et al. 2011; Eichholtz, Kok & Quiley 2013; Samandar 2015; Pomponi & Moncaster 2017
Water consumption	13%	US	Frey et al. 2012
	12%~25%	Global	Lippiatt 1999; Langston et al. 2008; Chau, Leung & Ng 2015; Samandar 2015; Dwaikat & Ali 2016
Waste generation	38%	Australia	Zuo & Zhao 2014
	25%~40%	Global	Langston et al. 2008; Chau, Leung & Ng 2015; Wong & Zhou 2015; Dwaikat & Ali 2016
GHG emissions	35%~40%	EU	Cellura et al. 2013; Asadi et al. 2014; Mikulic, Bakaric & Slijepcevic 2016
	40%~50%	US	Frey et al. 2012; Asadi et al. 2014; Menassa & Baer 2014
	41%	UK	Chidiac et al. 2011
	40%~50%	Global	Langston et al. 2008; Miller & Buys 2008; Azhar, Brown & Farooqui 2009; Woo, Wilsmann & Kang 2010; Ardente et al. 2011; Wilkinson 2012; Motawa et al. 2013; Chau, Leung & Ng 2015; Samandar 2015; Wong & Zhou 2015; Pomponi & Moncaster 2017

Regarding the massive negative impacts of construction and building related activities on the natural environment, researchers from different countries have focused on studying and analysing how to deliver successful sustainable construction and create a harmonious built environment for humans and protect the natural environment.

During the Final Session of the First International Conference of the International Council for Research and Innovation in Building and Construction (CIB) TG 16 on Sustainable Construction, in Florida in 1994, Kibert (1994) defined the objectives of sustainable construction as mitigating harmful impacts on the natural environment and improving indoor environmental quality. The definition of the objectives of sustainable construction is regarded as a milestone of applying the concept of sustainable development in the construction sector (Conte 2018). In addition, Kibert (1994) recognised criteria of sustainable construction that can be used to identify building materials, products and systems. He also established seven principles for sustainable construction: conservation, reuse, renewing/recycling, nature protection, non-toxics, economics, and quality. Integrating the established principles and different life stages of buildings, a conceptual model of sustainable construction was built as shown in Figure 2.1. It shows that sustainable construction has to consider various impacts on different life stages of buildings. From then, creating a sustainable built environment became a primary objective for the construction industry (Conte 2018).

Figure 2.1. Conceptual model of sustainable construction



Source: Kibert 1994

Udomsap and Hallinger (2020) conducted a study to review research on sustainable construction from 1994 to 2018. They analysed 2877 sustainable construction related documents (published in English) from 98 countries by using a bibliometric method. The analysis showed that the interest in sustainable construction is a global phenomenon. Anglo-American-European countries dominate with an increasing interest from Asia (Udomsap & Hallinger 2020).

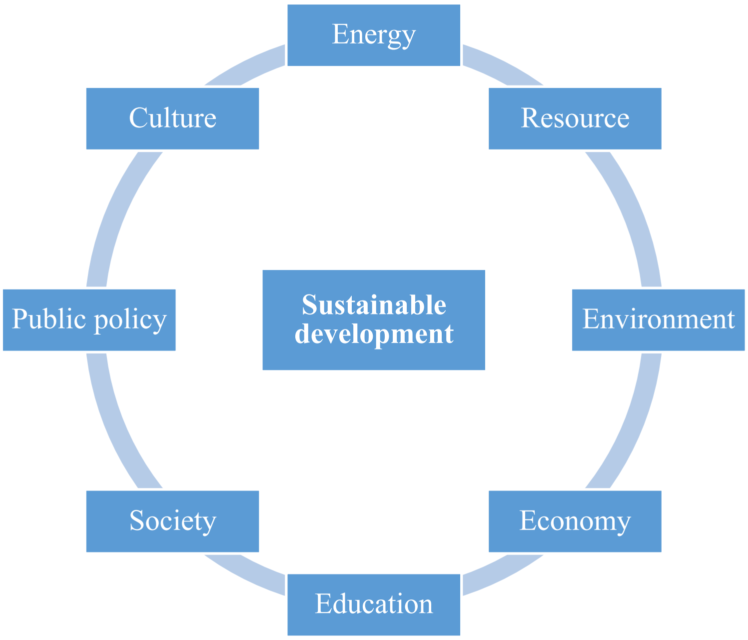
The first study about sustainable construction was in 1994, but over 80% of articles were published since 2010, which indicates that many areas of sustainable construction still remain to be exploited and studied (Udomsap & Hallinger 2020). By analysing different topics about sustainable construction through 2877 documents, Udomsap and Hallinger (2020) asserted that environmental and economic concerns are the main focuses and that there is a missing emphasis on social sustainability. In particular, there is a lack of standards for measuring and guiding the development of social sustainability in the construction sector. Udomsap and Hallinger (2020) forecast that the increasing research on sustainable construction would more than double in the next ten years. Their study emphasised the significance of sustainable construction, as by realising sustainable construction, it is possible to attain great progress and make a significant contribution to realising sustainable development in the whole of society (Udomsap & Hallinger 2020).

Indeed, buildings play an essential role in linking human daily life and the natural environment. By taking the perspective of a long-lasting coexistence of humans and nature, the improvement of the built environment can both mitigate unfavourable impacts on the natural environment, and also define a way to balance human life and nature (Conte 2018). Therefore, it is crucial to develop sustainable construction and improve the built environment to ensure a long future on the planet.

2.4. Sustainability dimensions

The various definitions of sustainable development indicate that different areas of our life are involved in sustainable development. Abu-Rayash and Dincer (2019) highlighted eight key areas covered by the concept of sustainable development as Figure 2.2 shows. These areas are interlaced in various ways. For instance, the economy field affects public policy while public policy influences the development and management of energy consumption. Their interplay makes it challenging to sort and analyse how human and social activities impact them. Therefore, they are commonly grouped into a manageable number of dimensions, and a series of relevant assessment criteria are identified for each dimension. For example, James (2015) studied urban sustainability and identified four dimensions of urban sustainability: economics, ecology, politics, and culture. Then, seven assessment criteria are identified under each dimension. Based on the evaluation of these assessment criteria, the level of urban sustainability can be measured.

Figure 2.2. The eight key areas covered by the concept of sustainable development



Source: Adapted from Abu-Rayash & Dincer 2019

Another four-dimensional model was implemented in studies by Dincer and Zamfirescu (2018) and Sadollah, Nasir and Geem (2020). Their studies were about sustainable development from the perspective of energy resources. Therefore, sustainable development is regarded as a synthesis of preservation of energy resources, environmental sustainability, economic sustainability, and social sustainability. Sadollah, Nasir and Geem (2020) explained that energy is a crucial factor in poverty reduction and the improvement of living standards. It should be integrated with the other three sustainability dimensions to pursue comprehensive sustainable development.

2.4.1. Three-dimensional model – triple-bottom line approach

Compared to the four-dimensional model, a three-dimensional model of sustainable development by integrating the environmental, economic and social dimensions is more widely recognised and applied (Purvis, Mao & Robinson 2019). Brundtland (1987) stated that economic and social development must be promoted simultaneously to eliminate world poverty and release limitations by the state of technology and social organisation on the environment's ability. Combined with the emphasis on preserving natural resources, the Brundtland report was believed to be the early proposal of the three-dimensional model of sustainable development (Gimenez, Sierra & Rodon 2012; Klöpffer 2008). One way to integrate environmental, economic and social dimensions to achieve sustainable construction is explained by Conte (2018):

- starting point (environmental dimension): to alleviate negative environmental impact by saving energy, reducing resource consumption, and controlling emissions and waste generation from construction activities
- means (economic dimension): to invest in construction activities to realise sustainable construction and a sustainable built environment
- outcome (social dimension): to achieve long-lasting development for society.

The three-dimensional concept was later adopted in the assessment method of sustainability called triple-bottom line (TBL) by Elkington, which is a new approach to an accounting framework (Elkington 1997). In triple-bottom line, the three main concerns are referred to as people, planet and profit, or the three Ps, by Elkington (1997). Due to the well-known definition of sustainable development by WCED (1987), and following intense debate and discussion about sustainable development, the three Ps were later developed into environmental, economic and social dimensions (Gimenez, Sierra & Rodon 2012). The common assessment criteria under the three dimensions are listed in Table 2.3 based on the study by Savitz (2013).

Table 2.3. Typical measures in triple-bottom line

	Economic	**Environmental**	**Social**
Typical measures	Sales, profits, return on investment	Pollutants emitted	Health and safety record
	Taxes paid	Carbon footprint	Community impacts
	Monetary flows	Recycling and reuse	Human rights; privacy
	Jobs created	Water and energy use	Product responsibility
	Supplier relations	Product impacts	Employee relations

Source: Savitz 2013

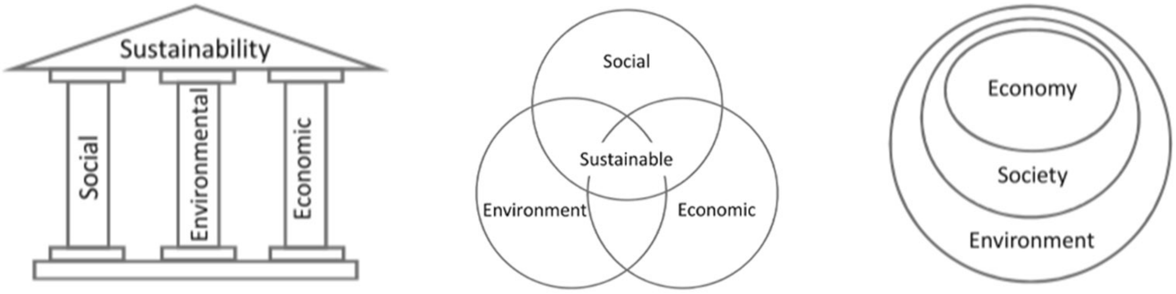
As a popular measuring approach of sustainable development, triple-bottom line is also implemented to assess sustainable construction performance. Gou and Xie (2017) stated that green buildings are evolving through the push of two main concepts – regenerative design and triple-bottom line. Regenerative design encourages improvements of positive impacts by design activities instead of reducing negative impacts, while triple-bottom line improves performance of green buildings by including different aspects of sustainable development in a process of assessment and decision making. Mathiyazhagan, Gnanavelbabu and Prabhuraj (2018) developed a sustainable assessment model based on the triple-bottom line approach, which can be used by construction companies in India to select suitable building materials by considering their impacts on environmental, economic and social dimensions. Jiang et al. (2019) conducted a study to analyse benefits and limits of modular prefabricated buildings in the construction stage using the triple-bottom line approach. The study outcomes showed that prefabrication can contribute to environmental improvement by saving 60% of steel, 56% of concrete, and 77% of formwork on site. However, it may cause some negative impacts on economic and social dimensions, including a relatively high initial cost compared to the conventional construction process, and limited labour availability.

In 2015, balanced development in environmental, economic and social dimensions was also advocated in the universal action by the United Nations (UN) – “Transforming our world: the 2030 Agenda for sustainable development” – to combat poverty, protect the planet, and make sure that all people can live in peace and prosperity by 2030 (Anderson et al. 2017; UN 2015). To conclude, the environment, economy and society are commonly recognised as three dimensions or pillars of sustainable development, which should be appropriately assessed and balanced when designing a new product or improving an existing product (Klöpffer 2008; Purvis, Mao & Robinson 2019). Therefore, this study also defines and assesses sustainable retrofitting in the environmental, economic and social dimensions.

2.4.2. Relationship among the three sustainability pillars

Based on the above discussion, it is generally accepted that sustainable development consists of three dimensions: environmental, economic and social. Therefore, it is important to understand the contents of each dimension, and also how the three dimensions are related. Based on the literature, the three sustainability dimensions are often expressed in one of three forms as Figure 2.3 illustrates.

Figure 2.3. Three dimensions of sustainable development



(a) Three pillars (b) Three intersecting circles (c) Concentric circles

Source: Adapted from Purvis, Mao & Robinson 2019; Thatcher 2013; Yolles 2018

Since the three dimensions always refer to three pillars of sustainable development, they are straightforwardly represented as three pillars of a building, as shown in Figure 2.3 (a) (Purvis, Mao & Robinson 2019; Thatcher 2013). However, this representation is criticised for considering the three dimensions separately and equally important. As discussed above, different aspects of sustainable development interact in different ways, and their importance changes with different stakeholders (Thatcher 2013) which is why more people prefer to show the three dimensions using three circles with overlaps, as shown in Figure 2.3 (b) and (c).

The Venn diagram in Figure 2.3 (b) symbolises the three sustainability dimensions. There are three circles with intersections, and sustainability exists in the area where all three circles overlap (Yolles 2018). The three intersecting circles indicate that the importance level of these three sustainability dimensions may vary in different circumstances. Figure 2.2 (c) symbolises the three dimensions as three concentric circles, showing the interdependence of the three sustainability dimensions. The concentric circles illustrate the relation between the three sustainability dimensions as the social development depends entirely on the environment, and harmonious economic development can be gained only by realising social and environmental priorities (Joumard & Nicolas 2010; Yolles 2018). It emphasises the significance of the environmental dimension, where the damage to the natural environment cannot be compensated for by capital increase. These two representations indicate the interconnection and interdependency among these three sustainability dimensions. Essentially, it is the issue of how the trade-off works between the three dimensions, or more specifically, what is the level of capital that can substitute for natural resources (Biely, Maes & Van Passel 2018; Purvis, Mao & Robinson 2019).

In this study, the representation of three intersecting circles is adopted to illustrate different opinions of decision makers on the level of importance of the three sustainability dimensions. In Figure 2.3 (b), different sizes of overlapping area indicate that the trade-off, or level of substitution, between the three dimensions will change with the different opinions of stakeholders. It mainly depends on how important stakeholders or decision makers of a sustainability project consider each sustainability dimension to be. In this study, the level of importance of the three sustainability dimensions needs to be decided to indicate the emphasis of any retrofitting. In addition, the different level of substitution between the three dimensions can be expressed by different views of sustainable development, as discussed in the following section.

2.4.3. Weak, strong, and very strong view of sustainable development

The previous section discussed the interplay relationship between the three sustainability dimensions. Based on different levels of substitution between capital and natural resources, three views of sustainable development are proposed: weak sustainability, strong sustainability, and very strong sustainability (Ayres, Van den Berrgh & Gowdy 2001; Kuhlman & Farrington 2010).

Weak sustainability implies that although the loss of some natural resources is unavoidable, this can be offset by increased capital (Kuhlman & Farrington 2010). However, this view can result in extreme sensitivity to either natural disturbances or economic shocks (Ayres, Van den Berrgh & Gowdy 2001). An example given by Ayres, Van den Berrgh and Gowdy (2001) can be used to explain the reason. In 1900, people in the island nation of Nauru became very rich from phosphate mining. However, as a result of continuous mining for over 90 years, about 80% of the island had been destroyed by the 1990s. When the Asian financial crisis suddenly happened in 1997, it wiped out most of the nation’s savings. The development of Nauru island followed the logic of weak sustainability. It also illustrates that it may be a one-way substitution between the natural resource and capital: once irreplaceable natural resources are transformed into manufactured or human capital, there is no way back to the previous situation (Ayres, Van den Berrgh & Gowdy 2001).

Standing in absolute opposition to the view of weak sustainability is very strong sustainability. It indicates that every natural environment component or subsystem, as well as every species and physical stock, must be protected (Ayres, Van den Berrgh & Gowdy 2001). However, very strong sustainability seems impossible in a culture that has created an industrial economy that relies on primary resources (Ayres, Van den Berrgh & Gowdy 2001).

Between weak sustainability and very strong sustainability, there is strong sustainability. In the view of strong sustainability, for those natural resources that are essential for our survival and the arrival of their tipping points cannot be prevented or slowed down by the current state of technological knowledge, a minimum amount of them must be preserved; for the environmental processes that are potentially reversible, they may fall under the criteria of weak sustainability (Ayres, Van den Berrgh & Gowdy 2001; Kuhlman & Farrington 2010). The view of strong sustainability can be used as a series of thresholds that cannot be crossed for realising sustainable development, and the impact assessment has to be constrained by these thresholds (Joumard & Nicolas 2010; Kuhlman & Farrington 2010). Actually, most significant variables in sustainability assessment are generated based on the thresholds of strong sustainability (Kuhlman & Farrington 2010).

To conclude, sustainable development is a matter of the degree of substituting natural resources for capital (Kuhlman & Farrington 2010). If the weak view is adopted, any natural resources can be substituted by capital. Oppositely, the loss of natural resources cannot be compensated by an increase in capital if the “very strong” view is adopted. By adopting the strong view of sustainable development, those natural resources that cannot be preserved or replaced by other resources based on the current state of technological knowledge should not be substituted by capital, but those that are potentially reversible may be substitutable by capital.

In this study, the strong sustainability view is adopted as the theoretical foundation for formulating the assessment process. First, the environmental, economic and social impacts of potential retrofitting activities are evaluated. Then, the importance of these three dimensions is determined to represent the trade-off or level of substitution between environmental protection and financial increase. By integrating the evaluation results of the three dimensions with associated weighting scores, the overall sustainability performance of potential retrofitting activities is evaluated. Details of the sustainability assessment are in Section 6.7 of Chapter 6.

2.5. Challenges of developing sustainable construction

The emergence of new terms like "smartness" or "resilience" questions whether the terms sustainability or sustainable development are still needed. Based on studies by the following scholars, sustainability is still needed. Increasing evidence shows that human activities are posing harmful impacts on climate change (Stocker et al. 2013). Moreover, the study by Motesharrei et al. (2016) suggested that the current carrying capacity of Earth cannot support the current rate of human development and population growth. Therefore, even though we have been immersed in the policies and practice of sustainable development for over 30 years, we still need to solve the problems that the Brundtland report posed (Conte 2018). In addition, there are several challenges that sustainable construction is facing and must overcome to achieve a wider application, as explained in the following sections.

2.5.1. High initial cost

First, the (perceived) high initial cost is one of the main obstacles to sustainable construction (Aghimien, Aigbavboa & Thwala 2019; Gunduz & Almuajebh 2020). Gunduz and Almuajebh (2020) identified critical success factors for sustainable construction by surveying professionals in the construction field worldwide to rank the importance level of 40 identified factors of successful sustainable construction. The result shows three essential factors that influence construction efficiency, one of which is finance. However, there is a general perception that the upfront investment in sustainable construction will be much more than in conventional construction. In the study by Rehm and Ade (2013), semi-structured interviews were conducted with 15 industry professionals across New Zealand. The collected responses indicated that all 15 participants believed that the construction cost of green buildings would be higher than for conventional buildings. Some people even assert that triple-bottom line is a zero-sum game because the cost premium of constructing green buildings (by considering all three sustainability dimensions) leads to negative income in the short term (Maltz, Bi & Bateman 2018). Consequently, investors and building owners avoid considering sustainable construction.

The initial cost of sustainable construction may be higher than traditional construction due to the relatively high cost of sustainable materials and new technologies (Cupido et al. 2010). In addition, the soft cost of green buildings, including consultants and the process of achieving a green building rating, also leads to a higher initial cost of green buildings (Cupido et al. 2010). However, this may not be true all the time. Based on the study by Zuo and Zhao (2014), green buildings in Australia rated as 4 stars may cost the same as conventional buildings, and ratings of 5 stars and 6 stars require construction cost premiums of 4% and 10% respectively. Dwaikat and Ali (2016) stated that green buildings are facilities that can cause less negative impacts on environment by consuming less natural resources[1]. To investigate the cost premiums of green buildings, they conducted 20 studies in Australia, New Zealand, the UK and the USA to compare costs between green buildings and non-green buildings. Their study found that two of the 20 studies recorded a cost premium for green buildings of over 20% more than conventional buildings, three studies between 10% and 20% (including 20%), three studies between 5% and 10% (including 10%), and five studies between 0% and 5% (including 5%). Five of the 20 studies indicated that green buildings have similar costs as conventional buildings, and the other two studies indicated cost savings by constructing green buildings.

Indeed, a green building does not necessarily mean much higher initial costs than conventional buildings. By adopting an integrative design method to build passive green buildings, energy savings and indoor comfort can be realised with less or no mechanical intervention. As a result, costly mechanical building systems can be downsized or even removed (Hawken, Lovins & Lovins 2013). Moreover, the upfront cost required to construct green buildings can be compensated by the cost reductions during the operation and maintenance stages (Zuo & Zhao 2014). Therefore, the high initial cost is a challenge in sustainable construction, but it may be a challenge based on perception only – what people think it will be, not what it is.

To reduce concerns about the high initial cost of sustainable construction, a proper sustainable design and comprehensive cost evaluation should be conducted at the early stage of construction (Kovacic & Zoller 2015). The life cycle costing of buildings should also be integrated, which can predict the potential capital return in the long term (Conte 2018; Maltz, Bi & Bateman 2018). Incentive policy, legislation and support from government, locally and nationally, can also help improve the feasibility and applicability of sustainable construction development

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Note 1: The authors listed different definitions of green building by other scholars, and they summarise them as the one that fits to their study.

2.5.2. A lack of attention to the social dimension

The second challenge is that not all the three dimensions are encapsulated in the assessment of performance of constructions as proposed under triple-bottom line (Goh et al. 2020). Previous studies have shown how environmental and economic impacts are assessed, but the social impact assessment is relatively vague and weak, regardless of the assessment methods or variables (Phillips et al. 2020).

For the environmental dimension, life cycle assessment (LCA) is the common method to assess the environmental impact of construction activities on different life stages of buildings (Dong & Ng 2016). The environmental impacts can include pollution of the natural environment based on different methods of life cycle inventory analysis (Kohler et al. 2010). In addition to LCA, many simulation tools are also available and can be used to estimate the environmental impacts of construction activities, especially for estimating energy consumption and carbon emissions. Building Information Modelling (BIM) is a popular simulation tool used to estimate energy use and predict performance for new buildings (Ilter & Ergen 2015; Woo, Wilsmann & Kang 2010).

For the economic dimension, in general, four different metrics can be calculated to measure whether the investment in construction projects is worthy (Cotter 2022): net present value (NPV), converting all cash flows during the life span of the building to current value based on the selected discount rate; equivalent annual cost (EAC), converting all cash flows to an equal amount per year over the life span of the building, or the annualised NPV; internal rate of return (IRR), the rate of discount at which the corresponding benefits and expenses are equal; and payback period, the number of time periods required to recover an investment’s initial costs from the net cash flows generated at the selected interest rate. Different methods can be selected for different purposes. The details are discussed in Chapter 4.

For the social dimension, there is still no unified or commonly recognised method to assess the social impacts of construction activities. In fact, there is not even consensus on what social impacts should be covered for assessing sustainable construction (Santos et al. 2017). Most studies focus on the impact of construction materials for assessing environmental performance and related costs, jointly or individually. The social dimension is commonly only briefly discussed, or even completely ignored. Goh et al. (2020) suspected the reason is that the social dimension is a human-centred aspect. For construction projects, stakeholders have different objectives and priorities. It is not easy to capture construction activities' impact on them, especially when the long-term perspective is adopted. However, to achieve sustainable construction, it is necessary to establish a balanced and optimal way to deliver sustainability in all the three sustainability dimensions (Klöpffer 2008; Purvis, Mao & Robinson 2019). To reach this goal, more effort is needed to investigate the details of the three pillars, both assessment methods and variables.

2.5.3. Difficulty of measuring trade-offs between different sustainability dimensions

As discussed in Section 2.2, sustainable development is a multidisciplinary concept. Therefore, decision making on sustainable construction needs to integrate the analysis of trade-offs between environmental, economic and social dimensions (Epstein, Buhovac & Yuthas 2015). However, the three dimensions are closely intertwined, and how to assess trade-offs between them is a critical issue. The first challenge of measuring trade-offs between sustainability dimensions is that there is no standard reporting method for holistically measuring buildings' performance in the environmental, economic and social dimensions (Goh et al. 2020; Phillips et al. 2020). For example, to measure the performance of a green office building, in some cases only construction costs are measured, but in others, the profit growth due to improved productivity from the construction activities is also included.

The second challenge is from the different measurement units of the three dimensions, which makes it difficult to calculate a cumulative outcome (Maltz, Bi & Bateman 2018). As a result, it is hard to compare and make a decision among different options (Slaper & Hall 2011). For example, energy consumption by a construction activity is estimated in units of MJ, financial investment is calculated in monetary units like dollars, and the social impacts can be estimated using value scores which are unitless. Different measurement units make it difficult to declare one activity can bring more sustainability benefits than another. Therefore, it is challenging to make decisions on sustainable retrofitting strategies.

Based on past studies, two solutions are proposed to solve the problem. One is converting all measures into monetary values, so impacts by a construction activity in the three dimensions can be measured based on a unified scale of money (Slaper & Hall 2011). However, it is not easy to find an agreed price for endangered species and limited natural resources when many people and organisations think they are priceless. Moreover, as discussed in Section 2.4.3, converting environmental impacts to monetary value may result in irreversible environmental damage. Therefore, this solution is not considered in this study. The other solution is normalising measures into universal or unitless values (Krajnc & Glavič 2005). In this way, the measurements for different dimensions are shown on the same scale, and a cumulative outcome can be reached for comparison and decision making. However, normalisation may lead to inaccuracies if the scale range is not properly determined. The typical range can be 0 to 1, 0 to 10, or 0 to 100. The range from 0 to 100 is more accurate than the other two if two decimals are required for the normalised results.

2.5.4. A lack of knowledge of sustainable construction

The last challenge in achieving sustainable construction is the requirement for knowledge, qualifications and skills about sustainable development by professionals, especially architects and engineers. They are the core group who make decisions and enforce the decisions into outcomes (Conte 2018). This challenge is more obvious in developing countries. Aghimien, Aigbavboa and Thwala (2019) stated that a lack of knowledge and understanding about sustainable development is the main obstacle to delivering sustainable construction. It is not only about professionals who cannot identify sustainable materials, make the right decisions, or adopt appropriate technologies, but also the public who lack the awareness of sustainable development. Consequently, the percentage of sustainable construction in developing countries is far less than in developed countries (Aghimien, Aigbavboa & Thwala 2019). By reviewing existing studies, the barriers from lack of knowledge to develop sustainable construction can be found in different locations around the world, as Table 2.4 summarises.

Table 2.4. Studies about barriers to develop sustainable construction

Location	Barriers
Cambodia	• Lack of skilled professionals • Lack of training and education, leading to a lack of awareness of environmental concerns
Canada	• Lack of consideration of sustainability criteria in the evaluation of bids • Lack of knowledge of local conditions
Chile	• Lack of knowledge on sustainable technologies
China	• Lack of awareness of environmental protection • Lack of awareness of reducing construction waste, especially from designers
Finland	• Lack of client understanding • Lack of knowledge and skills to conduct sustainable construction (procurement and tendering, timing, cooperation and networking, availability of methods and tools, and innovation)
Malaysia	• Lack of awareness of sustainable buildings • Lack of training and education about sustainable construction • Lack of professional capabilities/designers
UK	• Lack of proven technology alternatives

Source: Adapted from Durdyev et al. 2018; Ghisellini et al. 2018

Two methods are proposed to eliminate this barrier: properly selecting the set of sustainability assessment indicators, and training stakeholders with sustainability knowledge (Atanda 2019; Eberhardt, Birgisdottir & Birkved 2019; Hossain et al. 2020). Sustainability indicators are used to assess sustainability performance of products and services and this is the area that researchers normally focus on (Stanitsas & Kirytopoulos 2021). Sustainable indicators embed physical and social science knowledge into decision making, which can help decision makers, even policy makers, to simplify and clarify information (Atanda 2019). Therefore, to achieve sustainable construction, sustainability indicators that can include primary building impacts and evaluate specific aspects of the socioeconomic context should be used (Vilnītis, Lapsa & Veinbergs 2019). In addition, the selection of sustainability indicators is crucial to achieve a balance between sustainability dimensions (Wu et al. 2018). Stanitsas and Kirytopoulos (2021) also supported this point by emphasising the importance of balancing sustainability dimensions under the indicators "umbrella" in order to successfully achieve sustainable construction.

Another method to eliminate this barrier is training stakeholders in construction with sustainability knowledge (Eberhardt, Birgisdottir & Birkved 2019; Hossain et al. 2020). Training is an important tool to help stakeholders understand the aim, indicators, frameworks, guidelines and policies of sustainable construction, and government plays a vital role in promoting and popularising training in sustainable construction (Eberhardt, Birgisdottir &

Birkved 2019). The study by Atanda (2019) highlighted the content that should be covered in education of sustainability, including materials selection, energy sources, water and waste management, pollution, biodiversity, knowledge of the physical environment, understanding of human impact on the environment, and capability to address environmental issues. In addition, training in sustainable construction is particularly meaningful to building users, who normally have limited knowledge about sustainability. By understanding the tangible and intangible benefits of sustainable construction, their willingness to act towards sustainability may increase.

To conclude the above discussion, although there has been a steady increase in studying sustainable construction in the past three decades, challenges are still encountered including the perceived high initial cost, a lack of attention to the social dimensions, difficulty of measuring trade-offs between different sustainability dimensions, and a lack of knowledge about sustainable construction among stakeholders. To overcome these challenges and achieve successful sustainable construction, the below points are significant and should be satisfied:

- Environmental, economic and social dimensions should be integrated and balanced in an optimal manner.
- A long-term perspective should be adopted for investigating impacts on the three sustainability dimensions.
- The assessment method and assessment indicators should be thoroughly studied and determined for each sustainability dimension.
- A universal unit should be adopted for comparison and decision making.

2.6. Summary

Reviewing past studies on sustainable development and construction showed that sustainable development is a significant concept for realising a continuous development process without damaging the benefits to future generations. It covers various aspects of our daily life. Considering the extensive resource consumption and pollution generation of the construction sector, it is a crucial field for realising sustainable development for the whole society. Combining existing definitions about sustainable society and economy, and sustainable economic and environmental development, sustainable retrofitting is defined in this study as a process of reducing the cost of operating a building and increasing human wellbeing in ways that reduce deterioration of natural systems.

The environmental, economic and social dimensions are commonly recognised as three dimensions of sustainability. The popular sustainability assessment tool – triple-bottom line – also includes these three dimensions to assess sustainability performance of construction and buildings. Regarding different levels of substitution between capital and natural resources, three views are proposed: weak view, strong view, and very strong view. The weak view implies that the loss of natural resources can be offset by increased capital. In the view of strong sustainability, for those natural resources that are essential for our survival and where the arrival of their tipping points cannot be prevented or slowed down by the current state of technological knowledge, a minimum amount of them must be preserved; for the environmental processes that are potentially reversible, the loss of them may be offset by increased capital. In the very strong view, every natural environment component or subsystem, as well as every species and physical stock, must be protected. In this study, the strong view of sustainability is adopted to design assessment of sustainability performance of retrofitting activities. The level of importance of environmental, economic and social dimensions is determined to represent the trade-off or level of substitution between environmental protection and economic increase.

This chapter identified four challenges of achieving sustainable construction: perceived high initial costs, a lack of attention on the social dimensions, difficulty of measuring trade-offs between the three sustainability dimensions, and a lack of knowledge of sustainability. To overcome these challenges and realise sustainable construction, four suggestions are given based on existing studies. First, the environmental, economic and social dimensions should be integrated and balanced in an optimal manner. Second, a long-term perspective should be adopted for investigating impacts on the three sustainability dimensions. Third, the assessment method and assessment indicators should be thoroughly studied and determined for each sustainability dimension. Fourth, a universal unit should be adopted for comparison and decision making.

The next chapter presents a review of the performance of existing office buildings and sustainable retrofitting and discusses why sustainable retrofitting is an effective solution for improving existing office buildings' sustainability performance.

Chapter 3. Sustainable retrofitting of office buildings

3.1. Introduction

The previous chapter discussed the significance and necessity of sustainable construction and implementation of triple-bottom line to assess the environmental, economic and social sustainability of construction. Continuing the topic, this chapter discusses the necessity of improving the sustainability of existing buildings, especially office buildings, due to their extensive energy consumption and carbon emissions, and massive environment pollution (Che et al. 2019). Retrofitting is recognised as an effective remedy for the poor performance of existing buildings, and can be implemented to reach sustainability goals (Krstić-Furundžić, Vujošević & Petrovski 2019). To justify this statement, this chapter first investigates the current environmental, economic and social performance of existing buildings based on information derived from the literature (Section 3.2). Then, the reasons for retrofitting are analysed by comparing demolition and construction of new buildings, with the discussion of benefits and barriers of retrofitting (Section 3.3). Lastly, common retrofitting activities for office buildings are introduced, highlighting the potential improvement from them (Section 3.4 and 3.5).

3.2. Current performance of existing office buildings

The performance of buildings declines over time of use, not only because of aging building materials and components, but also because stricter building regulations over time increase demands on buildings, such as the demand for better indoor environmental quality. The phenomenon is more obvious for office buildings because their performance largely relies on the operation of mechanical and electrical facilities and systems. With the large number of existing office buildings around the world, their poor performance has caused extensive negative environmental, economic and social impacts. The following sections discuss existing buildings' performance in these three pillars in greater detail.

3.2.1. Environmental performance

In most countries about 20% to 40% of total energy consumption is from existing buildings (Hong et al. 2019). The massive energy use by buildings causes about 8.6 Gt CO_2 emissions each year (Munarim & Ghisi 2016). According to 2021 Global Status Report for Buildings and Constructions (United Nations Environment Programme 2021), the building sector is responsible for about 47% of the global annual carbon emissions. More than half of the 47% is from building operation. Due to the increasing affordability and advancements in air conditioning technologies, the demand for thermal comfort is also increasing, leading to more energy consumption by buildings expected in the future (Luo et al. 2018). Energy use in buildings is significantly higher in cities with high-rise commercial buildings (Che et al. 2019). Che et al. (2019) found that buildings account for 64% of Hong Kong's total final energy use, and commercial buildings account for 43% of the total consumption. Australia, as a representative developed country, has been practising sustainability in the built environment for decades, but about one quarter of the total greenhouse gas emissions in the country originate from building-related activities, and about 12% of total emissions are from office buildings (Drosou et al. 2018; Wilkinson 2014). Similarly, about 40% of final energy consumption in the United States and the EU is attributed to the buildings sector (Toosi et al. 2020; Wagiman et al. 2020). According to Li et al. (2019), about 22% of the energy used in the United States is consumed by commercial buildings. In Europe, the floor area of non-residential buildings is up to about 25% of the total floor area, and 26% of the space of non-residential buildings is office buildings (Gimeno-Frontera et al. 2018). However, non-residential buildings have 40% more energy consumption than residential buildings in Europe (la Cruz-Lovera et al. 2017; Toosi et al. 2020).

The situation is worse in developing countries due to more construction activities and relaxed energy policies (la Cruz-Lovera et al. 2017). As the largest developing country, China is currently experiencing rapid urbanisation, leading to a dramatic increase in energy consumption and carbon emissions (Zheng, Yu & Wang 2019). The annual added construction area in China represents up to half of the world's building construction (Ding & Ying 2019). In China, about 28% to 34% of national carbon emissions are from the building industry, which is approximately equal to the total carbon emissions in the Middle East (He et al. 2020). According to World Data Atlas (Andrew & Peters 2021; Friedlingstein et al. 2021), in 2020, China's CO_2 emissions were 8.2 tonnes per capita, almost twice as high as the world's per capita emissions in the same year.

Definitions of building types vary by national context. In western countries public buildings mean government buildings. In China, public buildings are designed for people for a variety of public activities, including commercial buildings, transportation buildings, tourism buildings, office buildings, hotels, and others (Wei & He 2017). The energy consumption by public buildings in China is 5 to 15 times that of residential buildings (Xu, Chan & Qian 2012). This statement is supported by Guo et al. (2022), stating that the operation energy of existing buildings in China accounts for 22% of the total domestic energy consumption, and public buildings are the largest contributor.

Indeed, commercial buildings, primarily office buildings, are some of the largest energy consumers and carbon emitters (Krstić-Furundžić, Vujošević & Petrovski 2019; Niemelä et al. 2017). According to IEA (2021), in 2020 about 27% of global energy consumption in buildings was from non-residential buildings with about 37% of energy-related CO_2 emissions. There was a slight decline in CO_2 emissions from the building sector in 2020 (from 9.6 Gt in 2019 to 9 Gt in 2020), which was mostly caused by lower activity in the services sector due to the global COVID-19 pandemic (IEA 2021). As social activity resumes, consumption and emissions are expected to gradually increase back to the pre-pandemic level (IEA 2021). Therefore, it is still urgent to reduce energy consumption and carbon emissions in existing office buildings.

Water is a very valuable resource, and due to the growth of global population and change in precipitation patterns associated with climate change, water demands are dramatically increasing (Lani et al. 2018). The construction and property sector is responsible for about 12% to 25% of water consumption (Dwaikat & Ali 2016). The majority of water used in public facilities is for flushing toilets (up to 50%), and with taps and showers together accounting for up to 80% of all water use (Bertone et al. 2018). To reduce water consumption in buildings, solutions include either reducing water consumption by installing water saving fixtures, or using alternative water resources such as treated or recycled grey water, or rain water (Sousa, Silva & Meireles 2019). The building sector is also responsible for about 30% of resource consumption, 40% of raw materials, and 25% to 40% of waste generation globally (see Table 2.2 in Chapter 2).

In addition to impacts on the natural environment, the indoor environment of existing office buildings is another essential aspect for achieving a sustainable built environment (Niemelä et al. 2017). Office buildings are designed to provide a workspace for people who typically stay in the provided work environment for at least 8 hours every day (Che et al. 2019; Cheong et al. 2020). Considering this long-hour occupancy, thermal comfort, visual condition and acoustic comfort are crucial for both long-term workplace safety and the physical comfort of occupants (Cheong et al. 2020).

Work productivity, in addition to safety and comfort, is another vital aspect affected by indoor environmental quality (IEQ). A nationwide survey conducted in the UK with professionals in different sectors indicated that sound indoor environmental quality contributes to up to 20% improvement in productivity of the building occupants, which is equivalent to £135 billion per year (Horr et al. 2016). Correspondingly, poor indoor environmental quality can reduce working performance. Among the three aspects of indoor environmental quality, thermal comfort has the greatest impact on work productivity. For example, 21 ºC to 25 ºC is observed to be an ideal indoor temperature range for office buildings. Every 1 ºC above 25 ºC up to 30 ºC can cause a 2% decrease in productivity (Kaushik et al. 2020).

Acoustic comfort and visual comfort are two other crucial aspects impacting work performance in office buildings. Acoustic performance has an equivalent effect on an employee as the thermal performance. Horr et al. (2016) showed that a 2.6 dB increase in noise has the same impact on productivity as a 1 ºC increase in indoor temperature. Visual comfort of office occupancies mainly relies on indoor lighting performance. Several studies have shown that office lighting has a considerable impact on work performance (Kim, Wang & McCunn 2019; Ma, Lee & Cha 2022; Wagiman et al. 2020). Moreover, prolonged exposure to a harsh visual environment in office buildings can lead to both physical and psychological issues, such as fatigue, headaches, back pain, annoyance and stress (Ma, Lee & Cha 2022). Due to these impacts on occupants, poor indoor environmental quality of office buildings is one of the main incentives for organisations to conduct retrofitting projects (Newsham et al. 2013). Indoor environmental quality is recognised as a vital assessment criterion for measuring environmental performance of existing office buildings (Shrubsole et al. 2019; Yang et al. 2020).

In summary, existing office buildings are consuming massive amounts of energy, emitting large quantities of carbon dioxide, and causing unfavourable impacts on the natural environment. Moreover, indoor environmental quality of office buildings has great impacts on occupants’ physical and psychological health as well as work productivity. Considering the large number and long life span of existing office buildings, improving environmental performance becomes urgent for alleviating the impact on global warming and enhancing occupants’ comfort level.

3.2.2. Economic performance

The general economic performance of existing buildings is suffering mainly because of high operation and maintenance costs (Oregi, Hernandez & Hernandez 2017). Based on the international standard ISO 15685-5 (ISO 2017), these two types of cost occur during the operation stage of buildings. Past studies have estimated that operation and maintenance costs account for approximately 75% to 80% of the total costs in a building’s whole life cycle if the service life is 50 years (Hauashdh, Jailani & Rahman 2022). The operation cost can also be called an environmental cost because it includes fuel costs for heating, cooling, power, lighting, water and sewerage costs, and related environmental taxes (ISO 2017). Therefore, the economic dimension of an existing property is highly related to its environmental performance, and energy price is the most relevant factor of existing buildings’ economic performance (Cetiner & Edis 2014; Mikulić, Bakarić & Slijepčević 2016; Santos et al. 2019).

The HVAC system is responsible for a substantial portion of energy consumption in commercial buildings to provide indoor thermal comfort and good indoor air quality (Che et al. 2019). Based on existing studies, the HVAC system consumes up to almost half of energy use in commercial buildings and dominates peak electricity demand (Che et al. 2019; Department of Climate Change, Energy, The Environment and Water 2022; Kim 2017). Following the HVAC system, the lighting system is the second largest energy consumer in commercial buildings, responsible for about 20% of the total energy use (Jin et al. 2021). Due to the large amount of energy consumption, the operation cost from these service systems also accounts for a sizable amount of overall building costs (Department of Climate Change, Energy, The Environment and Water 2022). Moreover, due to the growing recognition of the importance of improving indoor environmental quality of office buildings for health, a good work environment, and higher productivity, expenditures have been rapidly increasing (Kibert 2016). In the US, the annual cost of improving indoor environmental quality for office buildings is estimated to be hundreds of billions of dollars (Kats 2003; Kibert 2016).

For maintenance cost, eight kinds of costs are included (ISO 2017): maintenance management; adaptation or refurbishment of the building; minor repair and replacement cost; major systems or components replacement cost; cleaning; ground maintenance; redecoration; and tax on maintenance goods and services.

The quality and performance of building components and systems tend to diminish over time if no intervention like refurbishment or retrofit is applied. Moreover, building maintenance practices are becoming more and more difficult due to the environmentally friendly requirements and regulations and more complex building systems (Hauashdh, Jailani & Rahman 2022). Therefore, whether it is to attain acceptable building functions or to overcome maintenance challenges by contemporary requirements of sustainable buildings, maintenance costs are increasing and represent a certain portion of the total cost during a building's operation stage. Based on the data collected by Consulting Engineer (2022), for most buildings, about 80% to 90% of maintenance costs are attributable to 30% to 40% of individual asset items. Therefore, considerable savings can be attained by improving the efficiency of these items.

In addition to expenses on operation and maintenance, the income of properties also relies on the price, quality and competition of the property in the market (Wilkinson & Remoy 2017). There is no doubt that an existing building becomes less marketable if its performance is poor, especially compared to newer buildings. Based on the above discussion, it can be concluded that with the expected higher energy price and fierce competition in the market for existing buildings, the investment opportunities for energy-efficient retrofitting will increase and it will become one of the driving forces for owners to retrofit existing buildings (Pombo, Rivela & Neila 2016).

3.2.3. Social performance

As discussed in Chapter 2, compared to the environmental and economic dimensions, the social dimension does not gain equal attention due to a vague definition and a lack of assessment methods (Phillips et al. 2020). Without a clear definition of social sustainability and what is covered in the social dimension, it is difficult to assess the social performance of a building as good or poor. Therefore, instead of discussing how existing buildings perform socially, different opinions about the social sustainability of buildings are summarised and discussed.

Tweed and Sutherland (2007) pointed out that the protection of cultural heritage is indispensable for achieving the social sustainability of buildings. The ability to preserve the cultural heritage embodied in existing buildings should be evaluated to alleviate or avoid the damage caused by construction activities. Valdes-Vasquez and Klotz (2012) stated that the social dimension reflects different aspects of the stakeholders of a project, including the mediation among employees, local communities, clients and the supply chain, to meet the demands of current and future populations and communities. Deuble and de Dear (2012) believed that cultural and behavioural factors, as part of the social context, are crucial for green building developments. Similar, Mateus and Bragança (2011) and Zuo and Zhao (2014) believed that the education level and awareness level of sustainable development of stakeholders, especially occupants, are important components of social sustainability. In the study by Samandar (2015), social sustainability is considered as a broad concept covering a variety of aspects including processes that can improve social health and wellbeing.

Even though different aspects are emphasised by different scholars, most aspects are related to people, particularly stakeholders. This point is also agreed by other scholars. Watson et al. (2016) stated that the social context can be expressed as building user group dynamics, which is an integration of institutional norms, culture and management. Wilkinson and Remoy (2017) and Parida et al. (2021) identified social aspects for office buildings, which are work-related flow, comfort, wellbeing and job satisfaction of occupants. Social sustainability essentially involves various social values that are influenced by different stakeholders (Liu & Qian 2019). In terms of a building project, it is supposed to meet the diverse requirements of multiple stakeholders involved in the whole project process including construction teams, suppliers, end users and local communities (Liu & Qian 2019).

It is normally difficult to quantify human-related content due to its “soft” characteristics. However, even though the advantages of social sustainability are intangible sometimes the benefits can be returned in many ways (Samandar 2015). For example, a study conducted by Onat, Kucukvar and Tatari (2014) assessed buildings’ performance in the UK using the triple-bottom line approach. In their study, three major social impacts were identified for commercial buildings which are the construction phase, electricity consumption, and commuting. Onat, Kucukvar and Tatari (2014) explained that the income of commercial buildings is heavily influenced by the construction phase. More than half of the tax categories of commercial buildings are about electricity consumption. Construction (43%) and commuting activities (34%) are the major sources of work-related injuries in commercial buildings. A similar study by Li, Ding and Runeson (2018) also confirmed that the social dimension covers a wide range of aspects, and that some financial benefits and environmental benefits can be achieved if the social performance of buildings is improved. Therefore, social sustainability is indispensable to achieve the overall improvement of sustainable buildings.

Based on the above discussion, construction activities generate various social impacts on individuals, communities, and even the whole of society. The wide coverage and the intangible characteristics of the social context make the social dimension challenging in pursuing overall sustainable buildings (Dendena & Corsi 2015). As an indirect way to preserve the cultural and societal assets that have been embodied in existing buildings, building retrofitting should not be carried out without social impact assessment (Jagarajan et al. 2017). However, researchers have not reached complete agreement on what social content should be included in the context of sustainable buildings. Any stakeholder-related factors can be selected as components of social impacts of buildings for different analysis. In this thesis study, the impacts of retrofitting construction on stakeholders, including building owners, tenants, people who visit the building, people who live or work in neighbouring buildings, and people who pass by the buildings (or the retrofitting construction) are considered. The selected social impacts are also checked against the impacts included in the environmental and economic dimensions to prevent double or triple counting.

3.3. Sustainable retrofitting

3.3.1. Definition of retrofitting

According to the Cambridge Dictionary (Walter 2005), retrofit means “to provide a machine with a part, or a place with equipment, that it did not originally have when it was built”. When it is used in the construction and property sector, retrofit refers to modification of existing buildings to make their facilities easy to operate, more efficient and with less impact on the environment (Hong et al. 2019). This may involve activities such as adjustment, reuse or upgrade to existing building envelopes and mechanical systems to meet new conditions or requirements (Bruce et al. 2015; Hong et al. 2019; Wilkinson 2014).

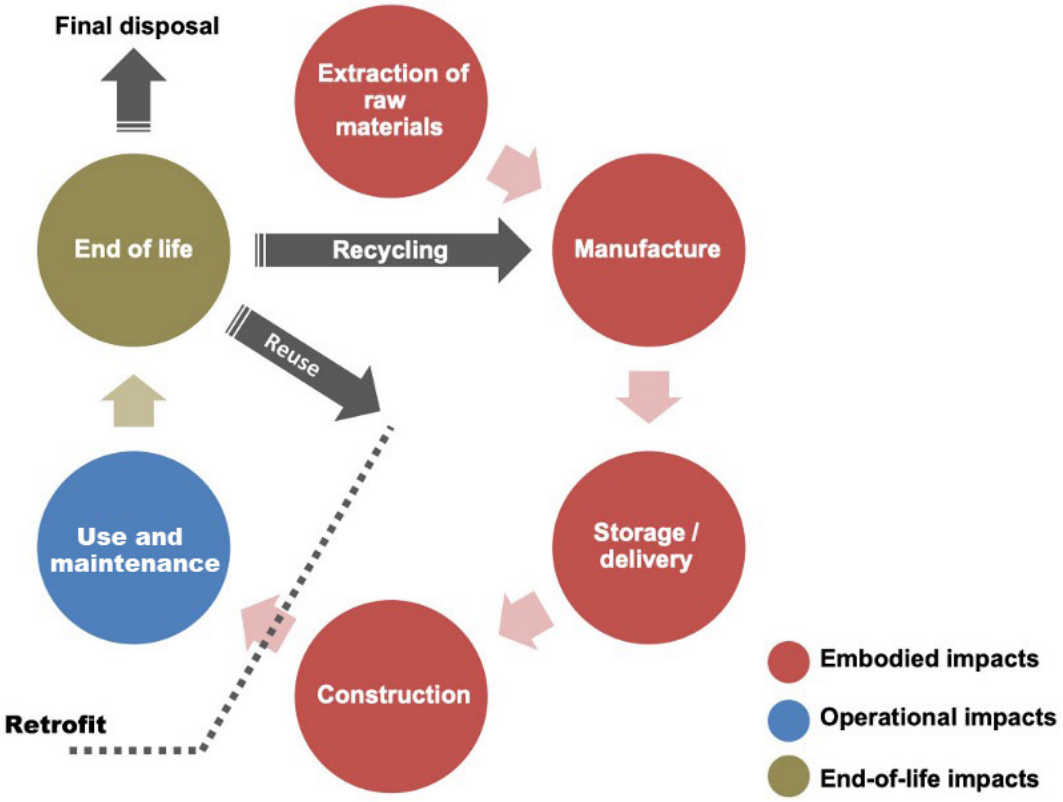
Apart from retrofit, there are other terms that are interchangeable for expressing a similar meaning but in different scales from repairing building fabric to refurbishing the whole building, including renovation, refurbishment and conversion (Wilkinson 2012; Zhang et al. 2021). Among these four terms, conversion is the easiest to distinguish because the function of existing buildings is only changed when building conversion is conducted (Remøy & Wilkinson 2012). In other words, a new use is fitted in the existing building via conversion, but not by the other three terms. In the conversion process, the building structure including loadbearing members would be affected, while the major structure would not be changed in retrofit and renovation projects, even though the intervention may encompass the whole building (Giebeler et al. 2009).

Renovation is defined as intervention activities that do not extend the existing building structure, nor change anything with new substitution (Giebeler et al. 2009). Therefore, the value and function of the renovated building will not change, but its quality may be improved to some degree. According to Brown and Teernstra (2008), renovation is part of the maintenance process with large investments to enhance building quality and maintain its basic function.

Similar to renovation, refurbishment is also a necessary intervention for maintaining existing buildings. According to the international standard ISO 15685-5 (ISO 2017), refurbishment cost is one component of maintenance cost. However, in contrast to renovation to keep the basic function of buildings, refurbishment is always adopted to meet new standards caused by increasing demands or new technical regulation (Giebeler et al. 2009). It is divided into three categories according to the degree of change: partial refurbishment, “normal” refurbishment, and total refurbishment (Giebeler et al. 2009). Partial refurbishment refers to changes involving only one component or one part of existing buildings. “Normal” refurbishment makes additions or changes to the entire building or at least one part of it. A total refurbishment project involves replacing the current infrastructure or upgrading all existing components of the building, and often involves demolition activities.

Instead of being regarded as a maintenance measure, retrofit is more like a new stage in the life cycle of existing buildings (see Figure 3.1) that can modernise outdated buildings to comply with current energy efficiency rules, building standards, and requirements for indoor comfort (Munarim & Ghisi 2016; Wilkinson 2012). The latest technologies are normally adopted in a retrofit project to prolong service life and improve the performance of existing buildings (Menassa 2011; Shaikh et al. 2017). Retrofit is regarded as an effective way to improve the sustainability level of existing buildings not only by improving buildings’ energy efficiency performance, but also by largely reusing existing components and structures with minor additions of materials and energy use (Jagarajan et al. 2017; Latham 2016).

Figure 3.1. Extended life cycle of buildings by retrofitting



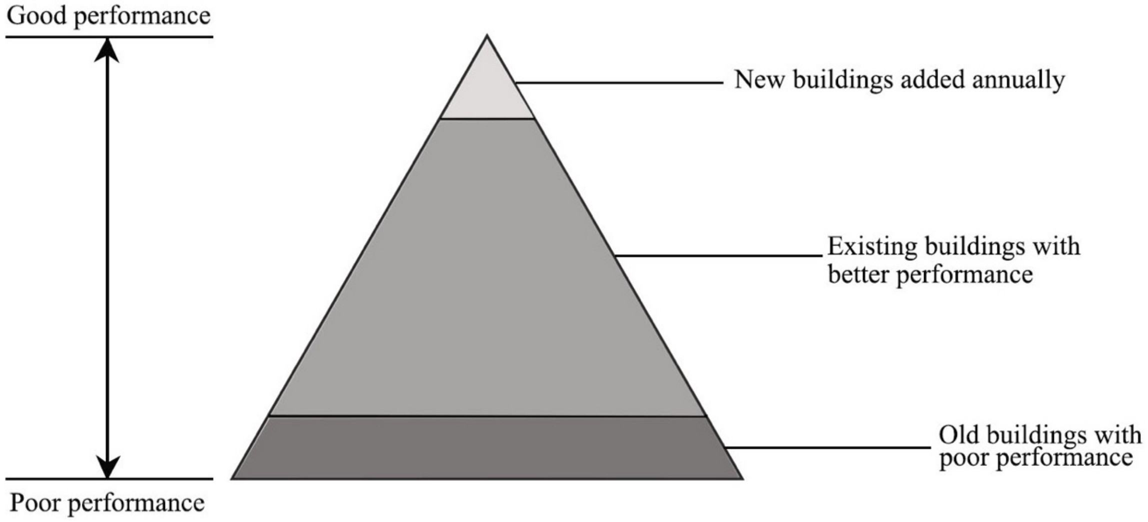
Source: Adapted from Munarim & Ghisi 2016

As discussed in Chapter 1, this study is designed to investigate how to improve the sustainability performance of existing office buildings, including how to upgrade building performance where no structural element would be affected. The expected outcome is that existing office buildings' sustainability performance can be effectively improved, embodied energy in existing structures can be preserved, and the service life of existing buildings can be reset. Therefore, the term "retrofit" is more specific and appropriate for use in this study.

3.3.2. Reasons for retrofitting

Atkinson (1988) introduced a "sinking stack" theory to explain the relationship between new buildings and existing buildings as Figure 3.2 shows. The new buildings are added at the top annually representing current building conditions, and old buildings with poor quality are at the bottom of the stack. With the passage of time, all buildings age, and resources and energy are needed to maintain their quality and performance. From the perspective of sustainable development, the existing buildings with very poor performance, at the bottom of the stack in Figure 3.2, should be removed from use. The quantity of new buildings should be minimised to reduce the energy and resources required in construction. Most resources and effort should be allocated to improve the performance of the existing stock in the middle of the stack in Figure 3.2.

Figure 3.2. Sinking stack theory



Source: Atkinson 1988

Buildings are a long-lasting product that require regular maintenance and renewal, but still cannot avoid becoming obsolete or redundant due to changing demands and regulations. Eventually, the obsolescent buildings are demolished and new buildings are built complying with current standards and regulation, but the obsolescence stage can be delayed by retrofitting (Ongpenga et al. 2020; Solanki, Rastogi & Paul 2022). The reason for preferring to retrofit is that, compared to demolition and new construction, retrofitting can provide a quicker delivery of sustainability in time and save energy (Thomsen & Van der Flier 2011).

First, retrofitting is a more feasible strategy than demolition because of the huge number of existing buildings around the world. Existing buildings may represent approximately 87% of buildings that we will use until 2050 (Wilkinson & Remoy 2017). In the UK, almost 85% of current buildings will be occupied until 2050 (Dowson et al. 2012). About 66.3% of buildings in the US and 75% in Europe were built before 1990 (Lee, Shepley & Choi 2019). Moreover, over 25% of existing stocks in Europe are older than 70 years and do not reach the requirement of energy efficiency in the new energy codes (Invidiata, Lavagna & Ghisi 2018; Vilches, Garcia-Martinez & Sanchez-Montañes 2017). Regarding the large quantity of existing buildings, the rate of new buildings added to total stock is only 1% to 2% annually (Ding & Ying 2019; Wilkinson 2012). Therefore, compared to demolishing existing buildings and building new ones, retrofitting seems a more feasible strategy to improve the sustainability performance of the whole building sector.

Second, retrofitting can improve performance more quickly than demolition new buildings (Wilkinson & Remoy 2017). As a product with a long service life, the negative impacts of buildings also last for a long time if no effective intervention is adopted. As discussed in Section 3.2, existing buildings are blamed for posing environmental, economic and social obstacles to overall sustainable development (Lee et al. 2020). With the large quantity, long service life, and massive negative impacts of existing buildings, compared to demolition, retrofitting can provide a faster process than demolition and then building a new building since the existing structure can be preserved, and existing infrastructure can be largely reused (Munarim & Ghisi 2016; Power 2010).

Last but not least, there is the promising potential of retrofitting to save energy and reduce carbon emissions, both embodied and operational. The operation stage accounts for about 70% to 90% of the total energy consumption in the whole life span of a building (Menassa & Baer 2014; Toosi et al. 2020; Yuan, Nian & Su 2019). Previous studies have shown that sustainable retrofitting can effectively improve the energy efficiency of existing buildings (Che et al. 2019; Hong et al. 2019; Luo, Lu & Ge 2021; Munarim & Ghisi 2016; Yin 2011). Savings of about 30% to 40% of energy use in existing buildings can be achieved by retrofitting (Hong et al. 2019). In commercial buildings, retrofitting can assist in achieving about 40% to 74% of energy saving (Yin 2011). Retrofitting existing buildings also has huge potential to reduce carbon emissions, estimated to result in a drop of up to 80% globally in 2050 compared to emissions in 2005 (Luo, Lu & Ge 2021).

With the big potential of saving operation energy and carbon emissions, the proportion of the impact from embodied energy and embodied carbon emissions is rising (Salehian, Ismail & Ariffin 2020; Toosi et al. 2020). For now, about 10% to 30% of the total energy consumption of a building is embodied energy (Ingrao et al. 2018; Toosi et al. 2020). It is estimated that the embodied carbon emissions in new buildings constructed between 2020 and 2050 will be equal to their operation carbon emissions (SDSN & FEEM 2019). Compared to demolition and new buildings, retrofitting can preserve the embodied energy and embodied carbon emissions in existing buildings by prolonging building use (Munarim & Ghisi 2016). If demolition is conducted, the embodied energy and embodied carbon will be wasted, and additional energy and emissions will be produced by new construction (Merlet et al. 2021).

In summary, given the low rate of new buildings being added to the building stock, the focus of saving energy and reducing carbon emissions should be on existing buildings. There are two strategies for the purpose: retrofitting existing buildings, or demolishing and replacing them with new buildings. Based on existing studies, retrofitting is often more desirable than demolishing buildings. First, the number of existing buildings is huge, and compared to demolishing them and building new ones, retrofitting is a more feasible strategy. Second, retrofitting can improve the sustainable performance of existing buildings more quickly than demolishing and re-building since the existing structure and infrastructure can be largely reused. Third, retrofitting can save operation energy consumption and carbon emissions, but also preserves embodied energy and embodied carbon emissions in the existing buildings, which is wasted if they are demolished. For these reasons, it can be concluded that rather than demolishing and re-building, retrofitting is more desired and effective to improve existing buildings' sustainability performance.

3.3.3. Benefits and barriers to retrofitting

In addition to the above-mentioned benefits, sustainable retrofitting also brings other tangible and intangible benefits. For the environment, retrofitting projects (without demolition) helps reduce landfill waste (Wilkinson & Remoy 2017). Retrofitting is also an effective strategy to reduce reliance on fossil fuel and contributes to the transition to a decarbonised energy system (Bleyl et al. 2019). From the economic perspective, retrofitting can contribute to higher rents and real estate values, lower running costs, higher work productivity, and lower vacancy rates. Eventually, the marketability of existing buildings can be improved (Bleyl et al. 2019; Bruce et al. 2015; Wilkinson 2014; Xu, Chan & Qian 2012). Kok, Miller and Morris (2012) conducted 14 case studies in different cities in the US showing that if the cost of retrofitting is USD 0.93/m^2 to USD 1.86/m^2, 8.79 kWh/m^2 to 14.65 kWh/m^2 energy can be saved annually, which can be converted to financial benefits of USD 0.14/m^2 to USD 0.23/m^2. From a social perspective, sustainable retrofitting can bring better indoor environmental quality, which is good for tenants' physical and psychological health (Lee et al. 2020). For office buildings, sustainable retrofitting is able to effectively improve work-related flow, reduce the absence rate, and improve job satisfaction, which helps achieve better organisation outcomes (Wilkinson & Remoy 2017).

Even though people are well aware of the variety of benefits from retrofitting, the annual rate of sustainable retrofitting is quite low, at about 0.4% to 1.2% of the total building stock in Europe (Tavakolan et al. 2022; Zhang et al. 2021). Lee, Shepley and Choi (2019) explained that the low rate is because of the high initial cost, insufficient incentives, lack of related information, lack of reliable advice, uncertain outcomes, and split benefits received by stakeholders, in which building tenants gain the benefits of retrofitting paid for by building owners. Indeed, sustainable retrofitting faces a number of challenges. To attain wide application of sustainable retrofitting, these challenges must be addressed.

First, even though the potential of saving energy and reducing carbon emissions by retrofitting is recognised, existing research aimed at improving the efficiency of buildings is still concentrated mainly on new buildings (Ding & Ying 2019). There is an absence of incentives through regulations and policies to improve existing buildings' energy efficiency and environmental performance (Munarim & Ghisi 2016). Munarim and Ghisi (2016) gave an example. In England, upgrades to existing buildings are subject to a tax of 17.5% (including Value Added Tax) while new buildings are exempt from Value Added Tax, which is assessed on expenditure or consumption. Additionally, most certification schemes for green buildings give priority to new buildings instead of existing buildings (Munarim & Ghisi 2016). For instance, in the LEED scheme, only 2 out of 144 points can be received for reusing at least 75% of existing structures.

Second, as discussed in Chapter 2, sustainable retrofitting also faces a financial barrier (Juliardi et al. 2019). Drosou et al. (2018) stated that even though technologies, tools and policies about sustainable retrofitting are already in place, only the confirmation of value added on existing properties can convince building owners to invest in sustainable retrofitting.

Third, a lack of knowledge is another challenge facing sustainable retrofitting (Bertone et al. 2016; Liu et al. 2020). Building owners are the essential promoter of sustainable retrofitting, but they normally have limited knowledge and poor awareness of sustainable retrofitting (Bertone et al. 2016). Moreover, retrofitting is a complicated process involving a wide range of technologies (Liu et al. 2020). Even if information about energy efficiency and water efficiency is available, the information is too complicated to analyse and choose (Bertone et al. 2016).

Lastly, the benefits split unevenly across stakeholders also lead to a low rate of sustainable retrofitting (Lee, Shepley & Choi 2019). Building owners pay for sustainable retrofitting, but tenants gain from the generated savings. Building owners would like to keep the capital costs of the building as low as possible (without giving much thought to energy and water saving), while tenants would like to maximise energy and water efficiency to save operation costs. As a consequence, sustainable retrofitting is often not considered (Bertone et al. 2016).

In conclusion, sustainable retrofitting can bring environmental, economic and social benefits for existing buildings, which helps improve the sustainability performance of the whole building sector. However, the rate of retrofitting existing buildings across the world is still low. Sustainable retrofitting faces various barriers. More research on the implementation of sustainable retrofitting is needed to maximise benefits and eliminate barriers.

3.4. Common retrofitting activities for office buildings

Retrofitting activities for office buildings refer to installing or upgrading building envelopes (external walls, windows and external shadings), energy-related systems (HVAC, lighting, lifts, energy supply system, etc.), water-related systems (water supply system, sanitary fixtures, etc.), and other electrical appliances by adopting the latest technologies (Bruce et al. 2015; Hong et al. 2015; Hong et al. 2019; Wu, Wang & Xia 2016; Xu, Chan & Qian 2012). Currently, building retrofitting is conducted mainly for energy saving and carbon emissions reduction (Che et al. 2019). However, there is no doubt that considerable water consumption in existing buildings can be reduced if suitable retrofitting activities are implemented (Bertone et al. 2018). By reviewing existing studies, commonly used retrofitting activities are mainly about upgrading and installing new components on building fabrics and building service systems, which are summarised in Table 3.1. The potential improvement from these retrofitting activities is discussed in the following sections.

Table 3.1. Common retrofitting activities for office buildings

Parts retrofitted	Retrofitting activities	Potential improvement	Reference
External walls and roofs	A1. Install/Upgrade insulation of building envelopes	• Reduce energy demand • Reduce carbon emissions • Increase indoor thermal comfort	Bruce et al. 2015; Hong et al. 2015; Krarti & Deneuville 2015; MOHURD 2015; Braulio-Gonzalo & Bovea 2017; Drosou et al. 2018; Illankoon, Tam & Le 2018; Lee et al. 2019; Zheng et al. 2019; Australian Government 2020; Chen et al. 2020; Kumar et al. 2020
Roof	A2. Adopt extensive green roof	• Reduce energy demand (mitigate the heat island effect) • Reduce carbon emissions • Reduce air pollution • Increase indoor comfort level	Bianchini & Hewage 2012; Peri et al. 2012; Besir & Cuce 2018; Shafique, Kim & Rafiq 2018; Aboelata 2021
Windows	A3. Replace existing windows with energy efficient windows	• Reduce energy demand • Reduce carbon emissions • Increase indoor thermal comfort	Krarti & Deneuville 2015; Cuce 2018; Drosou et al. 2018; Zheng et al. 2019; Evangelisti et al. 2020; Fulton et al. 2020; Haule et al. 2020; Dabbagh & Krarti 2021; Simko & Moore 2021
	A4. Install sun shading devices	• Reduce energy demand • Reduce carbon emissions • Increase indoor thermal comfort • Improve indoor visual comfort	
Management and control system	A5. Install building management control system (BMCS)	• Reduce energy consumption • Reduce carbon emissions	Yildiz, Bilbao & Sproul 2017; Drosou et al. 2018; Chen et al. 2020
Lifts	A6. Upgrade lifts to more energy efficient ones	• Reduce energy consumption • Reduce carbon emissions	De Almeida et al. 2012; Bogach & Wang 2013; Carrillo et al. 2013; Al-Kodmany 2015; Zheng et al. 2019; Ali et al. 2021
HVAC system	A7. Upgrade parts of existing HVAC system	• Reduce energy consumption • Reduce carbon emissions • Improve indoor air quality • Improve indoor thermal comfort	Bogach & Wang 2013; Bruce et al. 2015; Hong et al. 2015; Krarti & Deneuville 2015; Nguyen 2017; Che et al. 2019; Ding & Ying 2019; Far & Far 2019; Hong et al. 2019; Lee et al. 2019; Zheng et al. 2019; Energygovau 2020; Lu et al. 2021; Simpeh et al. 2021
	A8. Replace existing HVAC system with more energy efficient one		
Lighting system	A9. Install motion sensors for lighting system	• Reduce energy consumption • Reduce carbon emissions • Improve indoor visual comfort (greater luminescence and better colour rendering)	Stansbury & Mittelsdorf 2001; Dubois & Blomsterberg 2011; Lecamwasam, Wilson & Chokolich 2012; Bogach & Wang 2013; Bruce et al. 2015; Krarti & Deneuville 2015; BEEX 2017; Drosou et al. 2018; Riyanto et al. 2018; Beccali et al. 2019; Han et al. 2019; Hong et al. 2019; Zheng et al. 2019; Haule, Chaiwiwatworakul & Chirarattananon 2020; Wagiman et al. 2020
	A10. Replace fluorescent bulbs with T8, T5 or LED		
	A11. Install daylight dimming control system		
Energy generation equipment	A12. Install PV panels	• Reduce traditional energy (electricity) demand • Reduce carbon emissions	Akhimien et al. 2017; Nguyen 2017; Drosou et al. 2018; Belussi et al. 2019; Hong et al. 2019; de Cunha & Aguiar 2020; Wang et al. 2020; Chahidi et al. 2021

Water system	A13. Install water control system	• Reduce water consumption	Friedler & Alfiya 2010; Liu & Ping 2012; Cook, Sharma & Gurung, 2014; Hong et al. 2015; Bertone et al. 2016; Nguyen 2017; Bertone et al. 2018; Balachandran, Mahanta & Samuel 2020; Metallidou, Psannnis & Egyptiadou 2020
	A14. Apply water-saving appliances and fixtures (taps, toilet flushing)		
	A15. Install water treatment system and reuse recycled water (storm, black and grey water)		

3.4.1. Install and/or upgrade insulation of building envelopes (A1)

Effective insulation of building envelopes can help downsize the required coverage area or reduce the working load of the HVAC system. Therefore, appropriate thermal insulation is crucial for saving energy consumption and providing a comfortable indoor environment (Illankoon, Tam & Le 2018). In warm climate regions, due to improved insulation performance, a HVAC system may not even be needed in winter, contributing to energy saving by reducing the heating loads. The application of upgrading or installing insulation of building envelopes can save up to 40% of the energy consumption of an office building (Chen, Hammad et al. 2020).

In Australia, thermal resistance, expressed as R-value, is used to rate the insulation effectiveness. The higher the R-value, the greater the insulation effectiveness (Illankoon, Tam & Le 2018). The R-value of an external wall is the summation of all the R-values of the material constituting the external wall. After retrofitting, the R-value of the external wall should be greater than the limitation regulated by the National Construction Code (NCC) (ABCB 2019). In Green Star, Australia's national green building rating tool, up to 5 out of a total 20 points are allocated for energy saving by improving insulation performance, which indicates the significance of building insulation (Illankoon, Tam & Le 2018).

In China, instead of R-value, U-value is used to measure the insulation effectiveness. In contrast to the R-value, a higher U-value represents poorer insulation performance. The limitation of the U-value is different based on different climate zones and building categories. In China, there are five climate zones: severe cold region, cold region, hot-summer cold-winter region, hot-summer warm-winter region, and temperate region. Public buildings (non-residential buildings) in China are divided into two categories, A and B. According to the national design standard for energy efficiency of public buildings (MOHURD 2015), category A includes single buildings with an area more than 300 m^2 and building groups with each building area less than 300 m^2. Category B includes single buildings with an area less than 300 m^2. The U-value of the building's envelope after retrofitting should be smaller than the limits for these two categories provided in the national design standard (MOHURD 2015). Table 3.2 shows the largest U-values for public buildings in category B.

Table 3.2. Limit U-value for buildings in category B in China

	U-value (W/(m²•K)			
	Severe cold region	**Cold region**	**Hot-summer cold-winter region**	**Hot-summer warm-winter region**
Roof	≤0.35	≤0.55	≤0.70	≤0.90
External walls (including opaque curtain walls)	≤0.45	≤0.60	≤1.0	≤1.5
Windows	≤2.2	≤2.5	≤3.0	≤4.0

Source: MOHURD 2015

In a field study in Guangzhou China, a hot-summer warm-winter region, Song et al. (2017) measured an office building to indicate how much energy can be saved by different retrofitting activities on the building envelope. They created 27 scenarios to measure the different level of improvement on energy saving. By increasing thickness of insulation material to 4 cm and 10 cm, 0.49% and 0.83% of energy consumption can be saved respectively. These energy saving ratios can be applied for evaluating energy saving by the same retrofitting activity on buildings in this climate zone. However, it is important to note that the effect of energy saving by increasing the thickness of insulation materials can only be realised in a certain range (Braulio-Gonzalo & Bovea 2017). If the thickness of insulation materials is too small, the heat resistance ability will be poor. The energy saving ability from the increased thickness of insulation materials cannot compensate for the increased embodied energy of the insulation materials if it is too thick (Braulio-Gonzalo & Bovea 2017).

Reviewing existing studies (Braulio-Gonzalo & Bovea 2017; Chen, Hammad et al. 2020; Kumar et al. 2020) shows that cellulose, fibreglass, rock wool and polyurethane are four commonly used insulation materials for external walls and roofs. A case study by Chen et al. (2020) to evaluate the performance of these four insulation materials by implementing them on a house in Australia showed that cellulose is the optimal insulation material if embodied energy is the only objective considered, but fibreglass can contribute to the lowest energy requirement compared to the other three. Polyurethane has the best performance in insulation effectiveness, however it also has the biggest embodied energy of the four materials.

Existing buildings have illustrated the tremendous contribution to energy conservation by improving the insulation performance of building envelopes (Hong et al. 2019). With the great capacity of energy saving, the cost of improving insulation can be considered less. For example, if expanded polystyrene (EPS), a common insulation material, is used, the cost is about AUD 342 per metre square of insulation area (Braulio-Gonzalo & Bovea 2017). In Australia, the maintenance cost of building insulation ranges from 13% to 29% of the total life cycle cost (Illankoon, Tam & Le 2018).

3.4.2. Install green roof (A2)

A green roof is highly recommended for improving buildings' energy efficiency (Hong et al. 2019). Two kinds of green roof are available: intensive roofs and extensive roofs (Shafique, Kim & Rafiq 2018). The intensive roof is more like a roof garden with a thick layer of soil, leading to more weight and high cost. If an intensive roof is constructed on an existing building, the structure of the building has to be strengthened. Compared to an intensive roof, an extensive roof is more applicable for existing buildings. Only a thin layer of soil is needed, and minimum maintenance is required (Shafique, Kim & Rafiq 2018). Therefore, a green roof in this thesis study refers to an extensive roof only. The common material for constructing an extensive roof is polymer, which is light and cheap. There are six layers from top to bottom: vegetation, growing medium, water retention, drainage, root barrier and roof assembly (Shafique, Kim & Rafiq 2018). The study by Bianchini and Hewage (2012) calculated the air pollutants from the recycled and non-recycled polymer for both intensive and extensive roofs. Tables 3.3 and 3.4 illustrate the calculation data for extensive roofs only. The expected operation life of green roofs is 40 to 55 years (Bianchini & Hewage 2012). Based on these provided data and the area of the green roof, the amount of materials and air pollution can be calculated.

Table 3.3. Data for constructing a typical extensive roof

Layers	**Materials**	**Density (g/cm^3)**	**Thickness (cm)**
Root barrier	Low density polyethylene (LDPE)	0.92	0.05
Drainage	Semi-crystalline polypropylene (PP)	0.95	1.50
Water retention	Polymeric fibers	0.95	1.00

Source: Bianchini & Hewage 2012

Table 3.4. Amount of substances released to the air per 1 kg of polymer for green roof

Substance	**Unit**	**Weight (kg)**			
		Non-recycled		**Recycled**	
		LDPE	**PP**	**LDPE**	**PP**
NO_2	Kg	$3.8x10^{-3}$	$3.0x10^{-3}$	$-2.22x10^{-3}$	$6.75x10^{-26}$
SO_2	Kg	$5.3x10^{-3}$	$3.79x10^{-3}$	$5.03x10^{-3}$	0
O_3	Kg	$4.16x10^{-9}$	$2.88x10^{-4}$	$4.16x10^{-9}$	$6.75x10^{-26}$
PM_{10}	kg	$4.75x10^{-3}$	$4.06x10^{-4}$	$4.75x10^{-3}$	$6.75x10^{-26}$

Note: LDPE is low density polyethylene; PP is semi-crystalline polypropylene
Source: Bianchini & Hewage 2012

Green roofs have been regarded as an effective retrofitting activity to reduce buildings' cooling energy. The study by Aboelata (2021) showed that green roofs can reduce buildings' cooling energy by 5% to 15% in France, Singapore, Shanghai and Iran. Specifically, extensive roofs can mitigate the cooling energy of buildings by 1.3% to 13.3% (Aboelata 2021). In general, green roofs can reduce 80% of heat penetration into building roofs in summer, which contributes to 2.2% to 16.7% reduction of energy consumption compared to traditional roofs in summer (Besir & Cuce 2018). Green roofs can also effectively reduce a building's carbon emissions with an annual carbon capture in a range of 0.375–30.12 kg carbon/m^2 (roof area) (Besir & Cuce 2018). Green roofs can also improve indoor air quality and acoustic comfort, since the indoor environmental quality is largely affected by the proximity to outdoor sources (Barmparesos et al. 2018; Aboelata 2021). Green roofs can protect roof structures from extreme outdoor temperatures and large temperature fluctuations (Barmparesos et al. 2018). Moreover, green roofs also work as acoustic insulation to mitigate diffracting sound waves over roofs and reduce sound transmission through the roof system (Van Renterghem 2018).

3.4.3. Upgrade windows (A3 & A4)

Highly insulated windows not only save energy consumption by reducing heating or cooling requirements, but also contribute to a steady indoor comfort and better wellbeing and health for occupants (Simko & Moore 2021). Two values are commonly used to measure the insulation performance of windows: U-value and solar heat gain coefficient (SHGC). The definition of U-value is in Section 3.4.1. SHGC is a fraction (from zero to one) that represents the proportion of incident solar radiation passing through a window (Dabbagh & Krarti 2021). Windows with high SHGC allow more solar radiation to pass through. Therefore, a high SHGC is desired in a heating dominated climate such as northern China for the "free" heating offered by solar radiation. Conversely, a low SHGC is preferred in a cooling dominated climate such as Sydney in Australia for keeping the indoor temperature cool (Cuce 2018; Simko & Moore 2021).

Generally, two strategies can be adopted individually or jointly: replacing existing windows (glazing with/without frames) with energy efficient ones, and installing sun shading devices.

Replacing existing windows with energy efficient windows depends on types of glazing and materials of frames (Simko & Moore 2021). Double glazing is safer, more airtight, and soundproof than single glazing (Hong et al. 2019). Filling the gap between window panes with argon or krypton gas can lower thermal conductivity by 34% compared to air in the gap (Berardi 2018). A low emittance (low-e) coating that can suppress radiative thermal heat is normally installed to gain a low SHGC (Simko & Moore 2021). Simko and Moore (2021) conducted a case study using a house in Australia to analyse energy saving and cost efficiency performance of energy-efficient windows in Australia. Based on their study, the thermal conductivity and cost of different combinations of glazing types and frame materials are summarised in Table 3.5. Apart from double glazing, installing triple glazing or multiple glazing windows, or adding secondary glazing on existing windows are also potential activities for better energy efficiency, and thermal and acoustic insulation performance compared to single glazed windows (Bulut et al. 2022). However, the price of these activities varies in different countries.

Table 3.5. U-value, SHGC and cost of different options of glazing types and window frames in Australia

Frame option	**Double glazing**			**Double glazing with low-e coating**		
	U-value (W/m^2•K)	**SHGC**	**Cost (AUD/m^2)**	**U-value (W/m^2•K)**	**SHGC**	**Cost (AUD/m^2)**
Timber	2.6	0.5	609	1.7	0.17	703
Aluminium	3	0.64	508	2.1	0.36	585
Thermally broken aluminium	2.8	0.64	529	1.8	0.36	608
uPVC	2.3	0.41	356	1.7	0.24	410

Source: Simko & Moore 2021

Installing sun shading devices to reduce heat gain from solar radiation is also an effective way to save energy use. This retrofitting activity is more recommended in tropical areas where solar radiation is abundant. Sun shading devices include external vertical shading, horizontal shading and internal blinds (Haule, Chaiwiwatworakul & Chirarattananon 2020). Appropriate application of sun shading devices can reduce incoming heat fluxes by about 39% which needs to be compensated by an air conditioning system (Evangelisti et al. 2020). The exact energy saving by sun shading devices can only be estimated by considering the particular situation of the building such as location, climate, shape coefficient of the building, window/wall ratio (WWR), etc.

Valladares-Rendón, Schmid and Lo (2017) investigated the potential energy saving by using sun shading devices in Singapore, South Korea and Taiwan. They found that for a rectangular building in Taiwan, about 8.92% energy saving can be achieved if a horizontal shading is applied. In South Korea, a south-facing building with a horizontal shading is able to lower the cooling loads during May to September by 14.81 kWh/m^2 (or 19.7% energy demand reduction). If a fixed tilted overhang with 60º adjustable slats is installed on the south-facing windows, about 66% energy saving can be achieved (Valladares-Rendón, Schmid & Lo 2017). In Singapore, the yearly space cooling loads can be lowered by 21.2% in a building by installing the overhang with 30º incline downward on the west-facing windows (Valladares-Rendón, Schmid & Lo 2017). Sun, Cui and Jiang (2018) conducted a case study in the cold zone of China that found about 5.32% potential energy saving in a building if external shading is applied.

In addition to energy saving, sun shading devices are used for a variety of other purposes. They can maintain acceptable visual and thermal comfort conditions, protect against heat and glare on sunny days, and reduce cooling loads and lighting requirement (Stazi, Naspi & D'Orazio 2017).

3.4.4. Install building management control system (A5)

Installing a building management control system (BMCS) can control and monitor the use of electricity of related building systems like the HVAC and lighting system. It can automatically turn on and turn off these building systems according to the schedule of tenants and external weather parameters like ambient humidity, temperature and solar radiation (Yildiz, Bilbao & Sproul 2017). The basic BMCS strategy is to schedule the operation of the HVAC system and automatically turn it off during non-working hours, during holidays, and when the required indoor temperature is the same as the outdoor temperature, and fresh air only is provided. A BMCS monitors use of electricity by different consumers in real time, which can alert building managers to breakdowns and mistakes during the operation of these building systems to avoid electricity waste. The ranges of potential energy saving through the BMCS of the HVAC system and lighting system are 10% to 28% and 43% to 71% respectively (Chen, Zhang et al. 2020).

3.4.5. Upgrade lifts to more energy efficient ones (A6)

Lifts account for 1% to 15% of overall energy consumption by an office building, which is the lowest compared to other equipment because the consumption depends on the actual appliance (Ali et al. 2021). During peak time, lifts may consume about 40% of the energy use of a building (Al-Kodmany 2015). Advanced technology can be applied to both the hardware and software of lifts to achieve more energy saving. Energy efficient hardware of lifts includes alternating current (AC) motors and direct current (DC) motors, geared and gearless motors, machine-room-less technology (MRL), regenerative drives, elevator ropes, twin systems, double deck lifts, and LED lighting. Energy efficient software involves destination dispatching system, people flow solution, and standby solutions. These technologies do not only bring energy saving, but are also space saving and have more efficient traffic flow. New lifts with these advanced technologies can save about 30% of energy compared to conventional lifts (Al-Kodmany 2015; Carrillo et al. 2013).

3.4.6. Upgrade HVAC system (A7 & A8)

The HVAC is the biggest or second biggest energy consumer in a building, accounting for 30% to 80% of total energy use depending on HVAC options and climate zones (Simpeh et al. 2021). The main reason is believed to be the heating and cooling loss due to the poor insulation performance of building envelopes (Far & Far 2019). In Australia, about 40% of total energy used by buildings for meeting heating and cooling requirements is due to the poor thermal performance of buildings (DEWHA 2008). As for HVAC itself, related equipment and technology are also mature and have been widely applied for improving energy efficiency. The study by Simpeh et al. (2021) discussed measures for enhancing the energy efficiency of HVAC systems at a low cost, such as re-commissioning the system, to a major approach such as installing a smart management and control system which has a longer payback period.

Accordingly, the energy consumption by HVAC can be effectively reduced by two ways: reducing energy demand via improved insulation performance of building envelopes; and improving the energy efficiency of HVAC itself (Australian government 2022).

The strategy for improving buildings' insulation performance has been discussed in Sections 3.4.1 to 3.4.3. It is important to point out that energy saving from the HVAC system can only reach an optimum with the pre-condition that the building is well-insulated (Simpeh et al. 2021). Even though both improvements can benefit environmental saving, the efficiency of the HVAC system has a limited impact on the optimum insulation solution of building envelopes (Landuyt et al. 2021). In addition, the cost of a building's insulation is generally less than the cost of upgrading the HVAC system. Therefore, improving building insulation should be prioritised over improving the energy efficiency of the HVAC system.

To improve the energy efficiency of the HVAC system, different types of upgrade can be implemented: replacing part of the existing HVAC system with a more efficient one; and replacing the whole HVAC system with a more efficient one.

A case study of HVAC retrofitting was conducted by the Australian Government (2010) on a commercial building in Canberra, Australia. The adopted retrofitting activities for upgrading HVAC include:

- rezoning the HVAC system to improve occupant comfort and reduce conflict between the operation of cooling and heating systems
- converting the existing constant volume air distribution system to a semi variable air volume (VAV) system modulated at branch ducts, allowing variable rates of air flow depending on air conditioning requirement
- replacing an old reciprocating R22 chiller with a modern high-efficiency centrifugal machine with magnetic bearings and adiabatic cooling pads
- installing a modern building management system (BMS) to effectively control and monitor the new HVAC system.

The outcome showed that the retrofitting contributed to a 70% reduction in annual greenhouse gas emissions (about 786 tonnes $CO_{2\text{-eq}}$), AUD 120,000 saving on annual energy cost, and improvement in occupant comfort.

Che et al. (2019) conducted a similar study in Hong Kong, which illustrated that about 50% of energy use reduction can be achieved by the below retrofitting activities:

- adopting a sensor-based building management system for better ventilation and energy performance through auto-adjustment of the amount of air flow and cooling water based on sensed indoor CO_2 concentration and temperature
- adding dehumidification coils to remove moisture from the outdoor air to provide acceptable indoor thermal comfort in a hot and humid climate, saving energy from extra cooling and reheating processes
- updating a filtration system from an aluminium filter to a two-stage filtration system with aluminium filter and pleated filter to reduce the ingress of outdoor particles.

Similarly, a study by Lu et al. (2021) indicated that about 15% energy saving can be achieved by replacing the water-cooled chiller of the existing HVAC system with a more efficient one. In addition to energy saving and carbon emissions reduction, the HVAC system is also crucial to both indoor air quality and thermal comfort. In particular, the design and operation of the HVAC system greatly impacts the levels of indoor temperature and humidity (Che et al. 2019).

3.4.7. Upgrade lighting system (A9–A11)

About 26% of a building’s energy use is by the lighting system, making it the second largest electricity consumer (Haule, Chaiwiwatworakul & Chirarattananon 2020). There are three main strategies to reduce its electricity demand: retrofitting existing luminaires with energy efficient luminaries, such as LED; reducing the illumination level; and implementing control systems for better working efficiency (Dubois & Blomsterberg 2011; Wagiman et al. 2020). By appropriate retrofit, the energy consumption of a lighting system can be reduced by as much as 75%, with about half from upgraded fixtures, and half from the installation of controls (BEEX 2017).

By reviewing studies about lighting retrofitting, the below three activities are commonly used to achieve energy saving and indoor visual comfort:

- Installing motion sensors which can automatically turn on lights when motion is detected and turn off lights when people leave the area. With the installation of motion sensors, the electricity consumption is anticipated to be 30% to 40% lower than without sensors installed (Riyanto et al. 2018).

- Changing the lighting system to T5 or LED lighting system can provide great system savings on energy consumption (Lecamwasam, Wilson & Chokolich 2012). A study by Han et al. (2019) investigated energy saving by upgrading the lighting system of office buildings in South Korea and found that about half of the energy saving can be achieved if upgrading fluorescent lamps to LED.

- Installing a daylight dimming control system can automatically dim indoor lighting if day lighting is enough. By adopting an appropriate dimming strategy, a range of 31% to 60% of energy saving can be achieved (Beccali et al. 2019).

3.4.8. Install solar/PV-assisted units (A12)

Photovoltaic (PV) technology is the most widely used renewable energy system in the building sector due to the ability to provide on-site electricity (Belussi et al. 2019). Abundant solar energy provided globally also makes solar energy a feasible renewable energy. The sun provides the entire land surface with energy of about 5×10^{24} J each year (da Cunha & de Aguiar 2020). This amount is approximately 10,000 times greater than the real amount consumed globally each year (da Cunha & de Aguiar 2020). Renewable energy can help reduce reliance on energy supply based on fossil fuels and reduce associated carbon emissions. Installing PV panels can generate power, and also reduce annual cooling loads by about 38% (Wang et al. 2020). The limit of adopting PV technology for existing buildings is the availability of roof space to install PV panels (Belussi et al. 2019). The installation of PV panels to generate energy can reduce electricity demand by an office building by about 26% (Nguyen 2017).

Wang et al. (2020) investigated potential energy saving by three types of PV systems in 13 cities in China. When taking into account the double effect of shading and power generation the daily overall energy-saving efficiency was 63.35% for the horizontally-mounted PV roof, 62.73% for the tilted PV roof, and 59.54% for the firmly-attached PV roof. A case study by Chahidi et al. (2021) identified that in the Mediterranean climate about 16% of energy demand can be reduced in the cooling period by adopting a PV system. In conclusion, installing PV panels can reduce energy demand by existing buildings, but the effectiveness of power generation depends on the local climate and geographic conditions.

3.4.9. Upgrade water system (A13–A15)

Office buildings are a major consumer of urban water, and about 50% to 90% of water use in office buildings is for toilet flushing and cooling tower blowdown (Cook, Sharma & Gurung 2014). There are several activities available for improving water efficiency:

- Installing water control sensors can minimise water use from water taps, toilet flushing and urinals. The study by Nguyen (2017) illustrated that using water control sensors can achieve 4–5 litres water per flush of toilets and urinals, and a flow rate of 4–4.5 L/minute for tapware. This strategy can contribute to water saving of 20%–34% (Metallidou, Psannis & Egyptiadou 2020).

- Replacing existing water fixtures with more water efficient ones, such as a water system with a high-pressure toilet water tank, sub-water meter, water control sensors, leak detection monitors, and waterless urinals can reduce water use. Using water saving fixtures can achieve water conservation of up to 40% compared to traditional fittings (Balachandran, Mahanta & Samuel 2020).

- Installing a water treatment system to reuse stormwater, and/or recycle grey or black water can help reduce water use. Up to 50% of water consumption in office buildings can be treated on site and reused for toilet flushing and/or landscape irrigation (Friedler & Alfiya 2010; Nguyen 2017).

3.5. Interruption to building tenants

There is no doubt that sustainable retrofitting can bring environmental, economic and social benefits if an appropriate retrofitting strategy is designed and implemented. However, the retrofitting construction may cause interruption to tenants, and building owners may be afraid that tenants may terminate the lease because of it. In fact, the earlier the understanding of disruption in terms of type and extent, the better the disruption can be accepted or managed (Chaves et al. 2016). Chaves et al. (2016) categorised disruption to users into four types:

- disruption of utilities: gas, electricity, and/or water supply is disrupted
- disruption of traffic: internal traffic flow, and/or access to the building is interrupted
- disruption of physical space: physical comfort is interrupted, and/or work space is occupied by retrofitting construction
- disruption of internal environment: noise, dust, and/or debris from retrofitting construction.

These disruptions impact existing tenants to different extents. Tzortzopoulos et al. (2019) classified these disruptions into three levels: high, medium and low. High-level disruption refers to disruption inside buildings or interruption of normal work activities or building service provision. Medium-level disruption is caused by retrofitting activities that have a long construction duration, may lead to limited access to the building or service, or cause excessive unfavourable impact on the indoor environment. Low-level disruption is normally caused by retrofitting activities executed on the outside of buildings. Based on this classification of interruption, the retrofitting activities listed in Table 3.1 are recategorised in Table 3.6.

Table 3.6. Disruption levels of retrofitting activities

Disruption level	Retrofitting activities	Reason
Low-level disruption	A2. Adopt extensive green roof	Occurs outside of buildings
	A4. Install sun shading devices	
	A12. Install PV panels	
Medium-level disruption	A1. Install/upgrade insulation of building envelopes	Occurs outside of buildings Causes noise and waste
	A5. Install BMCS	Occurs inside building, but duration of limited access to building service is short
	A6. Upgrade lifts to more energy efficient ones	Occurs inside the building, but construction duration is relatively short and can be done during off-work hours
	A9. Install motion sensors for lighting system	
	A13. Install water control sensors	
High-level disruption	A3. Replace existing windows with energy efficient windows	Occurs inside building, and disrupts normal daily work activities
	A7. Upgrade parts of existing HVAC system	Disrupts use of HVAC
	A8. Replace existing HVAC with more energy efficient one	Disrupts use of HVAC
	A10. Replace fluorescent lamps with T5 or LED	Disrupts use of lighting
	A11. Install daylight dimming control system	Disrupts use of lighting
	A14. Replace existing water fixtures with more water efficient ones	Disrupts water use
	A15. Install water treatment system	Disrupts water use

Office buildings vary in terms of location, materials, construction type, energy type, age, size, and occupancy characteristics. Given the different situations of existing buildings and different levels of upgrade, the improvements from and the negative impacts of these retrofitting activities are different. Therefore, they should be selected by considering the specific condition and situation of the target building. The estimation of the environmental, economic and social impacts of retrofitting activities can help decide retrofitting strategies effectively.

3.6. Summary

This chapter first discussed the current performance of office buildings in the environmental, economic and social dimensions. Existing office buildings are responsible for large energy consumption, carbon emissions, and high operation and maintenance costs. On the social dimension, aging office buildings may lead to poor indoor comfort and less job satisfaction for building occupants. Considering the large quantity of existing buildings, their long service life, and the identified massive negative impacts, retrofitting is recognised as a better remedy than demolition and new construction. Sustainable retrofitting can quickly improve existing buildings' environmental, economic and social performance, and can also retain the embodied energy and embodied carbon emissions in existing buildings and avoid more of them being created by new construction. Based on previous studies, 15 common retrofitting activities for office buildings were identified and the potential contribution of each retrofitting activity was discussed. In addition to the contribution, the interruption to existing tenants by implementing these retrofitting activities was also discussed. Then, based on different levels of interruption, the identified retrofitting activities were categorised, which may help select suitable retrofitting activities.

The identified retrofitting activities can be used as a checklist. When the decision model developed in this study is implemented in practice, the retrofitting team can select suitable activities from it. However, the optimal retrofitting strategy can only be generated based on the estimation of the performance of the proposed retrofitting activities. Therefore, the next chapter reviews existing sustainable assessment methods and decision-making methods. By identifying the benefits and limits of each method, suitable ones are adopted to develop a conceptual model for retrofitting, as illustrated in Chapter 6.

Chapter 4. Sustainability assessment methods for buildings

4.1. Introduction

The last chapter discussed the current sustainability performance of existing office buildings and concluded that the poor performance of existing office buildings causes massive environmental pollution, operation costs and associated social impacts. To alleviate these negative impacts, sustainable retrofitting or demolition and new construction are two possible solutions. The existing studies show that retrofitting existing buildings can provide faster delivery of sustainable development compared to demolition and new construction. To assess the effectiveness of retrofit, this chapter discusses existing sustainability assessment methods for buildings. First, the assessment methods for evaluating buildings' environmental, economic and social impacts are introduced. Then, the assessment models incorporating two or more sustainable dimensions are discussed regarding their assessment framework and limitations.

4.2. Environmental impact assessment

Environmental assessment methods are important tools to assess and monitor buildings' environmental performance, and also link a building's environmental context to the decision-making framework of design strategies (Carvalho, Bragança & Mateus 2021; Sartori et al. 2021). Life cycle assessment (LCA) and green building rating systems (GBRSs) are two main approaches that can holistically evaluate the environmental performance of buildings (Mahmoud, Zayed & Fahmy 2019; Mattoni et al. 2018; Sartori et al. 2021). The assessment framework and associated benefits and limitations of these two approaches are discussed.

4.2.1. Life cycle assessment

Life cycle assessment (LCA) is popular as the only standardised method of environmental impact assessment (Dong & Ng 2016). It is widely used to quantify the environmental impact of a product or service from a life cycle perspective (Llatas, Soust-Verdaguer & Passer 2020). The international standards ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) are the foundation for performing LCA. These two standards govern four phases of LCA: the goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation of results. Each phase is discussed in the following sections.

4.2.1.1. Assessment framework: goal and scope definition

The first phase of LCA is to define the goal and scope of a study. This phase affects other aspects of an LCA study, including the selection of methods and adoption of details for LCI, the method of impact assessment interpretation, and reporting format (Desideri & Asdrubali 2018). Based on ISO 14040 (ISO 2006a) and 14044 (ISO 2006b), the following items should be identified to define the scope of an LCA study:

(1) Functional unit (FU): FU defines the quantification of the identified function and sub-functions of the studied system. It serves as the basis for the quantification of all inputs and outputs. In addition, FU allows assessment results of different products or services to be compared based on an equivalent functional performance (Souza et al. 2021). Different FU options for LCA studies of buildings are illustrated in Table 4.1. Among all the provided options, a square metre (m^2) of floor area is the most commonly used FU for building LCA (Saade, Guest & Amor 2020). In this study, the whole building (represented as gross floor area) is adopted as the functional unit.

Table 4.1. Functional unit options for LCA studies of buildings

Dimension	FU	Description
Space	m^2	Net floor area
		Gross internal area
		Gross floor area
		Air conditioned area or unconditioned area
Time	year(s)	Each year during lifetime
		Years during lifetime
Service	Occupancy	
Space per time	m^2/year	
Space per service	m^2/occupancy	
Space per time per service	m^2/year/occupancy	

Source: Adapted from Saade, Guest & Amor 2020; Souza et al. 2021

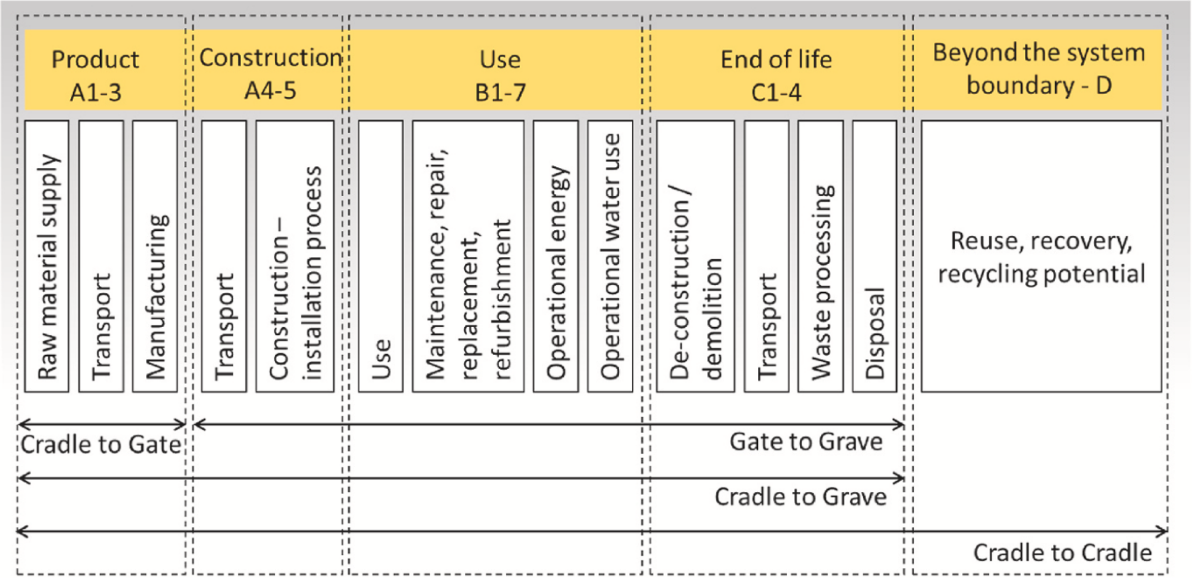
The space dimension considers the whole building, a section of it, or a specific amount of space, expressed as area (m^2) or volume (m^3). The time dimension refers to a building's life span. When addressing particular quality levels, the service dimension should be defined. If people use a building or items stored in a building, the FU per occupancy can be adopted. In cases of product manufacturing or service provision, per product output can be adopted as the FU (Souza et al. 2021).

(2) Reference study period (RSP): RSP is the time frame used to investigate the time-dependent characteristics of the object being evaluated (Desideri & Asdrubali 2018). For LCA studies of buildings, it refers to the use phase of a building, during which maintenance, repair and replacement activities will take place. Due to nontechnical factors like occupants' behaviour, local climate, surrounding environment and maintenance schedules, it is difficult to define an exact remaining service life for buildings. Therefore, a common time frame is used in research studies as a reference study period to assess buildings' performance. The common RSP used by research practice and international certification schemes, is 50 years or 60 years depending on different depreciation principles for construction investment (Rasmussen et al. 2020). However, a 50-year study period is typically used as a default RSP in LCA (Desideri & Asdrubali 2018, Rasmussen et al. 2020).

(3) System boundary: The boundary determines the unit process that is considered for the LCA study and indicates which stages and what processes during each stage are included (Birgisdottir & Rasmussen 2016). According to EN 15978 (CEN 2011), Figure 4.1 illustrates modular information for different stages of the building assessment contained in LCA. Different settings of system boundaries for LCA studies are also illustrated in EN 15978 (CEN 2011).

Based on different study purposes, different stages of buildings can be selected for formulating system boundaries. Common system boundaries include cradle to gate, where only the product stage of a product is considered (A1 to A3 in Figure 4.1); gate to grave, where the construction stage, use stage, and end-of-life stage are considered (A4 to C4 in Figure 4.1); cradle to grave, where the product stage, construction stage, use stage, and end-of-life stage are considered (A1 to C4 in Figure 4.1); and cradle to cradle, where all life stages are considered (A1 to D in Figure 4.1). Cradle to grave is the most widely used system boundary for LCA of buildings (Anand & Amor 2017).

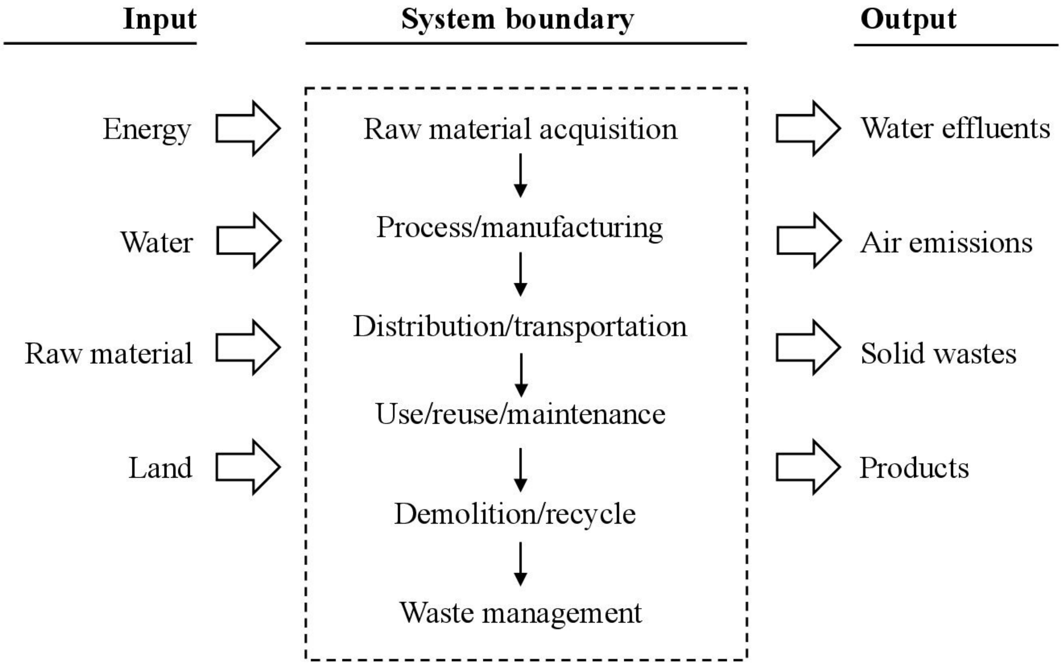
Figure 4.1. Modular information for different stages of the building assessment in LCA



Source: Adapted from Sartori et al. 2021

Following goal and scope definition, LCI analysis is conducted to create an inventory of flows that can be based on quantifying the inputs and outputs of the studied system in FU (Desideri & Asdrubali 2018). LCI of buildings is recognised as very complicated due to the different materials and processes involved and the dynamic nature of operating a building (Anand & Amor 2017). Figure 4.2 illustrates the LCI process applied to a building system, and the LCI phase is used for the data collection and modelling of the system (Hauschild, Rosenbaum & Olsen 2018).

Figure 4.2. LCI process applied to a building system



Source: Adapted from Hauschild, Rosenbaum & Olsen 2018

Three LCI methods are identified: the Process Analysis, the Input–Output (I-O) Analysis, and the Hybrid Analysis (Vilches, Garcia-Martinez & Sanchez-Montañes 2017). Process Analysis is a bottom-up approach that only includes processes within the boundaries of the studied product system. However, this method does not take into account the environmental impacts of inputs and outputs located outside of the system boundaries. As a result, omission of processes may be caused due to the “left out” impacts in the upstreaming stages (Lenzen 2008; Vilches, Garcia-Martinez & Sanchez-Montañes 2017). This method is suitable to compare different options of the same product or service, since the omission of processes will impact different options in the same way (Lenzen 2008).

The I-O Analysis is conducted based on national data, which makes it an appropriate method for national research (Vilches, Garcia-Martinez & Sanchez-Montañes 2017). However, if it is not certain the assessed product is representative, I-O Analysis may not be a suitable LCI method (Vilches, Garcia-Martinez & Sanchez-Montañes 2017).

The last method is Hybrid Analysis, combining Process Analysis and I-O Analysis (Vilches, Garcia-Martinez & Sanchez-Montañes 2017). In this method, the LCI is conducted based on Process Analysis and includes I-O data (Majeau-Bettez, Strømman & Hertwich 2011). There is a distinction between process-based Hybrid Analysis and I-O-based Hybrid Analysis in terms of the tier in which the I-O data is included (Treloar 1997; Vilches, Garcia-Martinez & Sanchez-Montañes 2017). Normally, the I-O-based Hybrid Analysis yields more adverse environmental impacts compared to the process-based Hybrid Analysis (Praseeda, Reddy & Mani 2015).

In addition to national data, environmental product declarations (EPD) or related databases can be used as sources of the secondary inventory data (Anand & Amor 2017). Numerous EPD certification programs are available in markets, including Eco Platform, International EPD, Bau-EPD, Inies, Global EPD, EcoLeaf, Milieu Relevante Product Informative (MRPE), Institut Bauen und Umwelt (IBU), Environdec, EPDnorge, NHO, dapC, PEP Eco PASSPORT, Korea Eco-Labeland, etc. (Desideri & Asdrubali 2018). As for databases, different LCI databases are available (shown in Table 4.2) and can be adopted to create LCI.

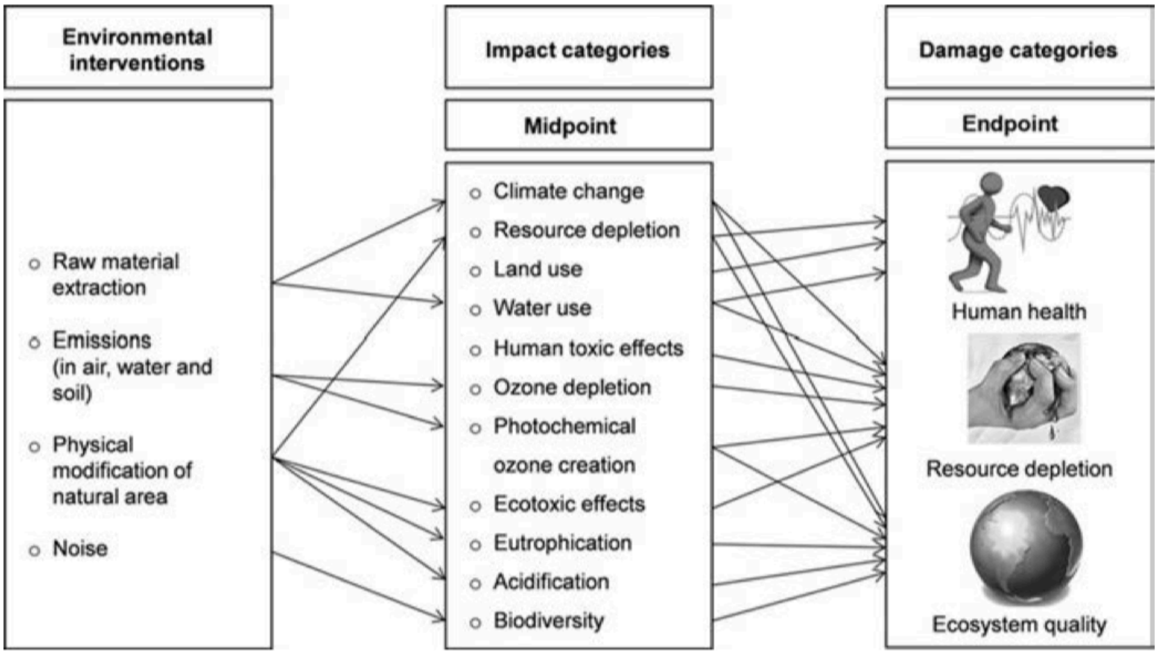
Table 4.2. Available LDI databases

Region	Database	Description
Global	Ecoinvent v3.1	International LCI database with most of the industrial, construction and transport processes, and systems
	GaBi LCA database	International LCI database with most of the industrial, construction and transport processes, and systems
	GEMIS 4.5	Free database that includes energy and transport processes, materials, processes, recycling, and waste treatment
	Agri-footprint	Comprehensive LCI database of feed, food and biomass, with around 3500 products and processes
	LC-inventories	Over 1000 process datasets, which are corrections, updates or extensions of Ecoinvent v2.2 database, created by ESU-Services and other authors
	NEEDS	Database designed for long-term environmental assessment, with around 800 processes of future energy supply systems, future material supply, and future transport services
Europe	Reference life cycle database 3.1	LCI data from front-running EU-level business associations and other sources for key materials, energy carriers, transport and waste management
	ELCD	Database of the Joint Research Centre (JRC) of the European Commission with more than 300 datasets on energy, material production, disposal, and transport
Denmark, Europe	IO-database	Input-output database based on the Danish national economic and environmental accounting statistics for 1999
	LCA Food	Danish database containing more than 600 datasets on basic food products and related processes from agriculture, aquaculture, fishery, industry, wholesale, and supermarket, including waste treatment processes
France, Europe	Diogen	Environmental impacts of the NF P 01–010 standards for materials used in the construction of civil engineering works
Germany, Europe	ProBas	More than 8000 datasets on energy, material production, transport and disposal, different data sources and data quality, focuses on processes within Germany
	Ökobau	German database for construction materials and building services provided by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB)
Luxembourg, Europe	Leitfaden	Public database of materials, components, and construction products
Spain, Europe	ITec	Economic information of the components, with more environmental data of each constructive element
Sweden, Europe	National LCA database	More than 500 well-documented LCI data sets in SPINE format for a wide range of industrial processes and household goods and services
US	LCA Commons	More than 18,000 datasets for US agriculture production and agriculturally derived products
	NREL	US–American database with around 300 datasets related to the production of materials, components, or assembly in the US
	Life-cycle inventory database	Provides individual gate-to-gate, cradle-to-gate, and cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component or assembly in the US
	Minnesota building database	Database of construction materials with rating about issues such as environmental, cost, health, sourcing, end of use or lifecycle thinking (based on Athena and BEES databases)
Canada	Athena database v.4	Comprehensive, comparable LCI databases for building materials and products

Source: Adopted from Desideri & Asdrubali 2018; Hauschild, Rosenbaum & Olsen 2018

After the LCI analysis, the next phase is life cycle impact assessment (LCIA). Characterisation factors of environmental impacts can be derived in two common ways: at midpoint level and at endpoint level (Huijbregts et al. 2017). At the midpoint level, 11 environmental problems are identified. From midpoint to endpoint where three areas of protection are identified – human health, ecosystem quality and resource scarcity, the damage pathway of environmental impacts are sorted as Figure 4.3 shows (Huijbregts et al. 2017). Accordingly, the environmental interventions can be assessed by linking LCI results via the impact categories (midpoint) to the damage categories (endpoint) shown in Figure 4.3 (Desideri & Asdrubali 2018).

Figure 4.3. The framework of environmental LCIA



Source: Adopted from Desideri & Asdrubali 2018

According to ISO 14040 (ISO 2006a), LCIA contains five elements, and the first three are mandatory:

(1) Selection: refers to selecting impact categories that should be part of goal and scope definition.

(2) Classification: refers to classifying inventory flows by assigning them to impact categories based on how much they can affect the chosen indicator.

(3) Characterisation: refers to using environmental impact assessment models to quantify the potential impact of the allocated elementary flows on the indicator of the category.

(4) Normalisation: is conducted to calculate the relevant magnitude of each characterised category indicator.

(5) Weighting: is a process of using numerical factors to express how severely each impact category is relevant to the other categories. With weights assigned, all the weighted impact scores can be aggregated into one overall environmental impact score for the studied system. It is especially useful if the LCA result is integrated with other condensed information like LCC to support decision making.

A variety of LCA tools are available for assessing the environmental impacts of buildings, which are listed in Table 4.3. Some of them are favoured because the data from design tools can be imported, and some are selected due to the ability to integrate multiple impact assessments.

Table 4.3. Common building LCA tools

LCA tools	**Included indicators**		
	Cost	**Environmental impact**	**Greenhouse gases**
Gabi	√	√	√
SimaPro	√	√	√
Umberto NXT LCA software	√	√	√
OpenLCA	√	√	
TEAM^{TM} 5.2	√	√	
EIO-LCA (Economic Input-Output Life Cycle Assessment)	√	√	√
Boustead Model		√	√
Athena (Impact Estimator for Buildings)		√	√
LEGEP-Life cycle Assessment	√	√	
Envest 2	√	√	
ECOSOFT		√	
BeCost	√	√	
BEES (Building for Environmental and Economic Sustainability)	√	√	√
EQUER		√	√
EcoEffect		√	√
ECO-BAT 4.0		√	

Source: Anand & Amor 2017

The last phase is interpretation of the result, a systematic process to identify, quantify, check, and evaluate information from the LCI and LCIA results. Finally, based on the results, a conclusion can be drawn, and the limits and recommendations should be given to the intended audience (Desideri & Asdrubali 2018; Hauschild, Rosenbaum & Olsen 2018).

4.2.1.2. Benefits and limitations

As the first and only internationally standardised environmental impact assessment method (Klöpffer 2003), LCA is being more widely used to assess potential environmental impacts of products, services and associated resource use (Birgisdottir & Rasmussen 2016). Three specific features of LCA are identified below (Finkbeiner et al. 2010; Hunkeler, Lichtenvort & Rebitzer 2008; Klöpffer 2003):

(1) The life cycle perspective: accounts for the impact from extracting and processing resources to distributing, transporting, consuming, and recycling and/or disposing of the product. The whole process has to be assessed for all relevant materials and energy flows.

(2) Setting measures in a functional unit: benefits of the system(s) are measured by quantifying all mass and energy flows, resource and land use, and any potential impact associated with these “interventions” in a functional unit.

(3) Comparative method: it is essentially a comparative method for decision making between alternatives. Also, it is used to compare the improvements of one system to the status quo.

LCA is also employed in the building sector, acting as a vital component of the evaluation of buildings’ environmental sustainability (Birgisdottir & Rasmussen 2016; Lei et al. 2021). In addition to assessing environmental impacts of building-related activities, LCA can also be applied to support decision making for better interventions or material selection toward environmental sustainability of buildings, and to compare environmental performance of two buildings with the same function (Desideri & Asdrubali 2018). However, some limitations prevent the broader use of LCA in building practice. Remarkably, four limitations are highlighted: uncertainty of LCI data input, uncertainty from a long life span of buildings, difficulty in providing a holistic assessment, and temporal issues (Desideri & Asdrubali 2018; Favi et al. 2018; Meex et al. 2018).

First, the environmental impact is assessed in LCA via inventory analysis based on a data process of input and output; thus, the accurate assessment heavily relies on the accuracy of LCI data input (Favi et al. 2018). Different from other products, each building is unique with a specific design and material use, which makes it impossible to standardise the assessment process. Even though the standards EN 15804 on EPDs and EN 15978 on the assessment of the environmental performance of buildings have been established for years, different interpretations of and additions to these standards are still made by various countries (Meex et al. 2018). Moreover, depending on different study scopes, input data may include information about the type and consumption of energy and materials from resource excavation, manufacturing and transportation to life stages of construction, operation and demolition. Even though numerous EPDs and LCI databases are available, environmental data for all materials is not available (Lei et al. 2021; Meex et al. 2018). Therefore, a lack of accurate LCI databases is reported as one of the major challenges of LCA studies (Desideri & Asdrubali 2018; Hunkeler & Rebitzer 2005; Llatas, Soust-Verdaguer & Passer 2020; Toosi et al. 2020).

Second, there are certain limits of LCA to forecast the future (Favi et al. 2018). Buildings have a long life span that can reach over a century, which increases uncertainty, particularly in the use stage due to refurbishment, repair, replacement, and occupants' behaviour (Meex et al. 2018).

Third, LCA simulation tools cannot provide a holistic environmental assessment. In most existing LCA software tools (Table 4.3), the focus is on the assessment of the embodied impact of materials, leading to the neglect of the estimation of operation energy demand (Meex et al. 2018). Moreover, these tools cannot consider occupants' comfort, wellbeing and health, thus failing to provide a holistic assessment approach and a complete LCA study (Desideri & Asdrubali 2018). In addition, there is a lack of studies applying LCA to building refurbishment (Meex et al. 2018; Vilches, Garcia-Martinez & Sanchez-Montañes 2017).

Lastly, the temporal issue in LCA is still a controversial topic (Lueddeckens, Saling & Guenther 2020). In LCA, the time value of environmental impacts is not considered, leading to most LCA studies making the assumption that environmental impacts occur with absolute certainty and constant magnitude during the study period (Zhang 2017). However, as discussed above, a building is a product with a long life span during which environmental impacts vary with the conduct of maintenance, repair and replacement activities, as well as changing use behaviours of occupants. Therefore, there is a need to distinguish short-term and long-term environmental impacts (Zhang 2017). However, this demand raises an issue of whether environmental impacts should be monetised or discounted. The proponents of monetising environmental impacts believe that environmental impact can be monetised as long as the following factors are taken into account when discounting environmental impacts: changes in damage magnitude; productivity of capital; pure time preference; and uncertainty (Hellweg, Hofstetter & Hungerbuhler 2003).

Nevertheless, monetising environmental impacts does not comply with the principle of intergenerational equity in which future generations deserve the same quantity and quality of natural resources and treatment as the current generation with a zero-discounting rate (Hartwig 2020). Moreover, in the discussion about the relationship among three sustainability pillars, it is neither desirable nor appropriate to put a price on natural resources, especially for intangible items. Therefore, most studies do not recommend economic discounting of environmental impacts. Thus, this thesis study uses the conventional environmental impact assessment method in which impact discount is not considered.

4.2.2. Green building rating system

Green building rating systems (GBRSs) are widely used to evaluate and verify sustainability of buildings (Shan & Hwang 2018). A GBRS usually consists of a set of explicit performance requirements that buildings must satisfy to be certified. In addition, it will also provide recommendations that may guide the project team in designing and constructing buildings to meet those performance requirements (Shan & Hwang 2018; Varma & Palaniappan 2019). GBRSs are widely used to assess building performance and have received close attention from construction authorities, businesses and academics around the world in recent years.

4.2.2.1. Green building rating schemes

Green building certification labels buildings as sustainable, high performance and energy efficient (Berawi et al. 2019). Since the end of the 20th century, hundreds of green building rating schemes have been introduced to assess, evaluate and categorise buildings at different levels (Cordero, Melgar & Márquez 2019; Varma & Palaniappan 2019). Chew and Das (2008) identified four generations of green building assessment methods: first generation refers to nominal type pass or fail certification systems; second generation refers to simple additive systems, in which assessment results are the addition of rating scores earned in different assessment categories; third generation refers to weighted additive systems, in which criteria are ranked by experts, and weightings are then assigned by analysing the data using a variety of methods; and fourth generation refers to tools which are operated based on cutting-edge concepts like the energy efficiency of buildings or life cycle impact and cost. Most GBRSs are second or third generation (Varma & Palaniappan 2019). GBRSs normally classify the impacts into different categories and assign a weight to each. The assessment is based on a system that assigns points to determine credits regarding their effect on the severity of environmental loads. Then, a final score is rated as a weighted score, and the degree of certification can be obtained by exceeding the required point thresholds (He et al. 2018).

The Leadership in Energy and Environmental Design (LEED, the USA), Building Research Establishment Environmental Assessment Method (BREEAM, the UK), and Green Star (Australia) are three GBRSs that are widely customised for use in different countries. Assessment Standard of Green Building (ASGB, China) is the national green building assessment standard in China, which is the world’s largest construction market. Table 4.4 summarises basic information about these four GBRSs which are discussed in detail in the following sections.

Table 4.4. Summary of four green building rating schemes

	BREEAM[1]	**LEED**[2]	**Green Star**[3]	**ASGB**[4]
Country	UK	US	Australia	China
Certification body	Building Research Establishment Group	US Green Building Council	Green Building Council of Australia	China's Ministry of Housing and Urban-Rural Development
First version	1990	1998	2002	2006
Latest update	2016	2019	2017	2019
Flexibility	83 countries	167 countries	3 countries	1 country
Impact categories and associated weights	• Management (11%) • Health and wellbeing (19%) • Energy (20%) • Transport (6%) • Water (7%) • Materials (13%) • Waste (6%) • Land use and ecology (8%) • Pollution (10%)	• Location and transportation (17%) • Sustainable sites (10%) • Water efficiency (11%) • Energy and atmosphere (33%) • Material and resources (13%) • Indoor environmental quality (16%)	• Management (14%) • Indoor environmental quality (17%) • Energy (22%) • Transport (10%) • Water (12%) • Materials (14%) • Land use & ecology (6%) • Emissions (5%)	• Safety and durability (17%) • Health and comfort (17%) • Life convenience (17%) • Resources saving (32%) • Environmental liveability (17%)
Maximum rating score	100 points (including extra 10 points for innovation)	110 points (including extra 10 points for innovation)	100 points (including extra 10 points for innovation)	110 points (including extra 10 points for promotion and innovation)
Certification levels	• Outstanding (≥ 85 points) • Excellent (70–84 points) • Very good (55–69 points) • Good (45–54 points) • Pass (30–44 points) • Unclassified (< 30 points)	• LEED platinum (≥ 80 points) • LEED gold (60–79 points) • LEED silver (50–59 points) • LEED certified (40–49 points)	• Six stars (> 75 points) • Five stars (60–75 points) • Four stars (45–59 points) • One to three stars (10–44 points)	• Three stars (≥ 85 points) • Two stars (70–84 points) • One star (60–69 points)

Source: Adapted from He et al. 2018; Suzer 2019; Liu & Leng 2021; Sartori et al. 2021

Note:

1. The weighting for BREEAM is based on BREEAM International New construction for non-residential buildings
2. The weightings for LEED is based on LEED V4.1 for BD+C New Construction
3. The weighting for Green Star is based on Green Star – Design & As built V1.3
4. The weighting for ASGB is based on ASGB - Design

BREEAM

BREEAM is the oldest protocol of GBRSs in the world (Cordero, Melgar & Márquez 2019; Mattoni et al. 2018). It was initiated for the construction stage of new structures in the UK. It now includes the whole building life cycle from the design stage to in-use and retrofitting and is available for global application (Mattoni et al. 2018; Varma & Palaniappan 2019). BREEAM consists of five systems: BREEAM–Community, BREEAM–New construction, BREEAM–In use, BREEAM–Refurbishment and fit-out, and BREEAM–CEEQUAL. Each system has a different scoring and weighting system (Cao 2022).

LEED

LEED is one of the most well-known GBRSs for evaluating sustainability for different life stages, including design, construction, maintenance and operation (Berawi et al. 2019; Mattoni et al. 2018). LEED consists of eight rating tools: LEED–Building Design and Construction; LEED–Operations and Maintenance; LEED–Interior Design and Construction; LEED–Homes; LEED–Neighbourhood Development; LEED–Cities and Communities; LEED–Recertification; and LEED Zero. It is regarded as the most influential and widespread international GBRS, which has been adapted into other national versions (Mattoni et al. 2018). Moreover, according to Sartori et al. (2021), LEED is the most cited of all green building rating schemes in the relevant studies. LEED is more like a design-guide scheme that provides the project team with a series of design strategies and measures (He et al. 2018). However, LEED is criticised as an energy-oriented environmental assessment tool since it gives the highest weight to the assessment criterion of energy and atmosphere. The overemphasis on energy efficiency may lead to other environmental impacts being overlooked (He et al. 2018).

Green Star

Green Star is a voluntary rating system for buildings and communities initially in Australia (He et al. 2018). It is also a popular GBRS, which has been customised with national versions in New Zealand and South Africa (Mattoni et al. 2018). Four Green Star rating tools are available: Green Star–Communities, Green Star–Design & as built; Green Star–Interiors, and Green Star–Performance (Green Building Council of Australia 2020). In contrast to LEED as a design-guide scheme, Green Star is a performance-based rating scheme that primarily uses quantitative data to anticipate environmental performance (He et al. 2018). Even though the two assessment criteria of energy and indoor environmental quality are assigned most weight in Green Star, environmental issues are treated in a relatively balanced way compared to LEED. It is noted that Green Star explicitly requires the process management assessment over the building life span (He et al. 2018).

Assessment Standard of Green Building (ASGB)

ASGB is the only national environmental rating system in China, the world’s largest construction market (He et al. 2018). ASGB is a single manual that is used to assess all civil buildings in China (Liu & Leng 2021). There are two assessment stages in ASGB. The first stage is the pre-assessment, which is the evaluation conducted after the construction design is finished. The second stage is the building assessment, which evaluates sustainability performance after the building is constructed (Liu & Leng 2021). Like Green Star, ASGB is also a performance-based rating scheme, which effectively encourages "appropriate" design innovation toward sustainability (He et al. 2018). Different from the previous version (established in 2016) focusing on resource saving, the latest update in 2019 emphasises the concept of being people-oriented by adding three new assessment categories: safety and durability, health and comfort, and life convenience (Cao 2022). It is noted that, unlike the other three discussed GBRSs, CO_2 reduction is only considered as a bonus in ASGB, and it is not a mandatory item. Additionally, no specific measures have been suggested to reduce CO_2 emissions in ASGB (Liu & Leng 2021).

4.2.2.2. Benefits and limitations

GBRSs have become increasingly significant in the development of green buildings due to their ability to assist buildings owners in baselining (i.e., setting a baseline measurement for future performance calibration), benchmarking (i.e., establishing a basis for comparing to competitors), decision making (i.e., developing a basis for selecting among alternatives), and documentation (i.e., documenting evidence to comply with sustainable regulations) (Shan & Hwang 2018). GBRSs are often used as a benchmark of quality, which aids in effectively communicating the goal and objectives of sustainable development with project stakeholders (Shan & Hwang 2018; Varma & Palaniappan 2019). In addition, Varma and Palaniappan (2019) stated that GBRSs can facilitate resource conservation and alleviate environmental impact while meeting users' needs. However, there are some limits to existing GBRSs, which have been discussed in relevant studies.

First, in the globalised world, the sustainability level of buildings should be able to be compared among different countries (Mattoni et al. 2018). Many studies have been conducted to analyse and compare various green building rating schemes. The finding illustrates that each rating scheme is established based on the local climatic and geographic condition, which differs from place to place. The variations have a significant impact on the selection of impact categories, scoring method, credit allocation, and especially, the weighting system for each rating scheme.

Consequently, different final scores may be achieved using different schemes to evaluate the same building (Karaca et al. 2020; Mattoni et al. 2018).

Second, many GBRSs claim that they are able to address the sustainable development goal holistically; nevertheless, most of them cannot even include all the three sustainability dimensions (Varma & Palaniappan 2019). According to Table 4.4, most impact categories in these four rating schemes focus on environmental impacts (Cordero, Melgar & Márquez 2019; Newsham et al. 2013). Therefore, it is stated that current GBRSs are still environmental-oriented, even energy-oriented tools (He et al. 2018; Lazar & Chithra 2020; Varma & Palaniappan 2019). LEED–Neighbourhood and BREEAM–Communities are two rating tools considering social and economic aspects. However, they are still criticised for insufficient analysis of social and economic impacts, and ambiguities in the weighting, scoring and rating system (Deng, Peng & Tang 2019). Without full coverage of the three pillars of sustainability, the trade-offs between energy and other sustainability issues cannot be carefully considered, leading to poor performance in other aspects, even though the building is certified as a green building (He et al. 2018). Therefore, the research gap is identified that a GBRS needs a framework that can implement the triple-bottom line concept of conserving the environment, improving the health, wellbeing and safety of building occupants, and being economically rational (Francis & Thomas 2022; Varma & Palaniappan 2019).

The last limit is that most existing GBRSs are designed for new buildings, and there is still a lack of knowledge and tools for sustainability design for existing buildings (Andersen, Jensen & Ryberg 2021). As discussed in Chapter 3, existing buildings are responsible for many negative environmental impacts, but the GBRSs designed for them are limited (Munarim & Ghisi 2016). For example, LEED–Operations and maintenance and Green Star–Performance are two common rating schemes for existing buildings. However, they are still criticised for focusing on the environmental dimension by assigning the largest weight to the assessment category “Energy” (Karaca et al. 2020; Solla, Ismail & Yunus 2016). Therefore, there is a need for GBRSs to evaluate existing buildings’ sustainability performance holistically.

4.3. Economic impact assessment

Life cycle cost (LCC) and cost benefit analysis (CBA) are two commonly used tools to assess the economic impacts of a product or service. The discounted cash flow needs to be calculated in both methods. However, it is for evaluating costs that may occur during the product's life span in life cycle cost, while evaluating the product's profitability in cost benefit analysis (Hoogmartens et al. 2014; Larsen et al. 2022). The benefits and limitations of each tool are discussed below.

4.3.1. Life cycle costing

The conventional economic impact assessments mainly focus on calculating the investment or the initial cost of a project, which is the primary concern of building owners or investors. However, the financial benefits returned in other life stages cannot be considered. Without potential financial return in the future being confirmed, building owners or investors may avoid adapting a project with a long life span due to the high initial cost. Therefore, the assessment method from the life cycle perspective should be used to holistically assess the economic performance of a building project. Life cycle costing (LCC) is a well-known economic appraisal that can estimate the costs of maintaining a facility over a period of analysis (Dwaikat & Ali 2018). The following sections discuss the details of life cycle costing and associated uncertain factors.

4.3.1.1. Background

Life cycle costing (LCC) has been developed and used for decades to assess a project's economic validity and attractiveness (Dong & Ng 2016). The initiation of LCC can be traced back to the 1960s when the US Department of Defence first carried it out to purchase high-cost military equipment (Fauzi et al. 2019; Guinee et al. 2011). It developed out of the need to thoroughly understand the financial flows over a product's life cycle. It allows decision-makers to consider not only the initial cost but also the costs of operation, maintenance and end-of-life treatment (Fauzi et al. 2019).

Kubba (2010, p. 325) stated that "LCC is a technique of combining both capital and operating costs to determine the net economic effect of an investment, and to evaluate the economic performance of additional investments that may be required for green building”. LCC is conducted to make more informed decisions about how well a building will function economically through its useful life cycle (Marzouk, Azab & Metawie 2018). It is primarily helpful to evaluate economic profitability and capital investments, and the LCC analysis from both a system and end-user perspective could be widely adopted in the building sector (Larsen et al. 2022). LCC takes into account all costs related to a product’s life cycle that are directly borne by any actor in the product’s life cycle, such as the supplier, producer and user (Fauzi et al. 2019; Hunkeler & Rebitzer 2005). In addition, it is also possible to include externalities anticipated to be internalised in the decision-relevant future (Hunkeler, Lichtenvort & Rebitzer 2008; Visentin et al. 2020). Generally, all costs over a lifetime of a building can be considered in LCC, which makes it a cradle-to-grave assessment method (Larsen et al. 2022). Based on the international standard ISO 15686-5: 2017 (ISO 2017), the major cost categories in LCC include design and construction cost, operation cost, maintenance cost, and end-of-life cost.

When conducting LCC in the construction and property sector, uncertainty is mainly from two factors – selection of discount rate and prediction of the building’s life span, which are discussed in the following sections. Different decision rules under LCC are introduced and a suitable one for this study is selected.

4.3.1.2. Discount rate

In LCC calculation, a discount rate is adopted to represent the time value of money (Jafari, Valentin & Russell 2014; Younis, Ebead & Judd 2018). The selection of the discount rate has a significant impact on LCC results. Sterner (2000, p. 388) stated that “choosing a discount rate which is too high will bias decisions in favour of short-term low capital cost options, while a discount rate which is too low will give an undue bias to future cost savings”. According to the International Standard ISO 15686-5 (ISO 2017), a discount rate, either real or nominal, should be included in the calculation to evaluate discounted impacts on investment. In addition, the discount rate may also be used to calculate the intermediate cash flows that are reinvested at the opportunity cost in the net present value (NPV) method (Arjunan & Kannapiran 2017). Based on the re-investment assumption, the intermediate cash flows can also be reinvested at the calculated internal rate of return in the internal rate of return (IRR) method (Arjunan & Kannapiran 2017). However, if the re-investment rate in IRR is not equal to the one adopted in the NPV method, conflicts can be caused (Arjunan & Kannapiran 2017; Keef & Roush 2001; Lohmann 1988).

The nominal discount rate is estimated considering inflation effects, while a real discount rate represents the true power of earning money without consideration of the inflation rate (Park 2016; Younis, Ebead & Judd 2018). The Fisher Equation (Equation 4.1) can be used to represent the relation between the three rates (nominal, real, and inflation rate) (Fisher 1907).

$$(1+n) = (1+r)(1+f) \qquad \text{Equation 4.1.}$$

Where,

n – nominal interest rate expressed as decimal
r – real interest rate expressed as decimal
f – inflation rate expressed as decimal

When LCC is adopted for comparing macro investment alternatives, the real discount rate is preferable to the nominal discount rate (Miraj, Berawi & Utami 2021) for three reasons. First, because it does not incorporate the effects of inflation, the real discount rate is more stable than the nominal discount rate. This is also supported by Eldomiaty et al. (2020) by stating that money illusion may be caused by using nominal discount rates to discount real cash flows, resulting in behavioural issues that cause inflation-induced valuation errors. Moreover, it is challenging to predict the inflation rate for a product with a long life span. Second, the calculation is very complicated and time-consuming if inflation is included in the calculation (Miraj, Berawi & Utami 2021). It means that every cash payment or income has been subjected to inflation and should be adjusted accordingly. This includes net uniform series, where every cash flow needs to be adjusted yearly. Third, inflation affects all types of products roughly the same way most of the time. Therefore, there is not much difference between the two methods in the desirability of any alternatives (Miraj, Berawi & Utami 2021).

It is noted that the discount rate may vary over the building's life span. However, it is usually assumed to be constant in LCC studies due to the uncertainty and complexity of predicting the value of money in the future (Jafari, Valentin & Russell 2014; Tavakolan et al. 2022). Therefore, a current real discount rate based on existing studies is adopted in this study to discount the economic impacts of each proposed retrofitting activity, and it is assumed to be constant during the study period.

4.3.1.3. Building service life

Building service life significantly impacts deciding the study period for a LCC study (Miraj, Berawi & Utami 2021). Jafari and Valentin (2015) examined the impacts of different lengths of remaining service life of retrofitted buildings on LCC results and concluded that retrofitting strategies can be more cost-effective if the remaining service life of the building is extended.

To estimate the service life of a building, two factors have to be considered – the physical lifetime of the building structure and the functional performance of the building system and facilities (Newton, Hampson & Drogemuller 2009). The building structure could remain for hundreds of years if proper maintenance is applied. Therefore, functional performance is the dominant factor determining the service life of a building. As one of the benefits from retrofitting (see Section 3.3.3 in Chapter 3), a building's service life can be prolonged to some extent. However, how long it can be extended is not known since the service life of the main building systems and facilities such as the HVAC system, lighting system, water system, building envelope, and doors and windows are different, and are affected by many factors such as quality of materials and components, users' behaviour, use frequency, and replacement frequency. For these reasons Goulouti et al. (2020) stated that uncertainty is always embedded in service life calculation.

Table 4.5 illustrates the life expectancy of typical building materials and building systems in Australia, which varies from 15 to 50 years. In LCC calculation, the building materials and components are replaced with new ones at the end of the life expectancy. Correspondingly, the recurrent costs occur at the time. Therefore, the building's remaining service life determines how many times the replacement of building materials and components is needed, and thus the total estimated replacement cost as well as the operation cost and maintenance cost. However, the periodic replacement of building materials and components may contribute to extending the building's service life, making it difficult to reach a consensus on a precise length for the life cycle study (Dwaikat & Ali 2018; Miraj, Berawi & Utami 2021).

Table 4.5. The life expectancy of building materials and building systems

Building materials/service systems	Life expectancy (years)	Building materials/service systems	Life expectancy (years)
Stucco	50	External sun shading panels	25–35
Stone veneer	50	Internal window blinds	10
Concrete poured-in-place	Building lifetime	HVAC	30
Brick, block, and stone	50	Lighting fittings	15
Precast concrete panel	30	Motion sensors for lighting system	15
Brownstone	40	LED lights	30
External thermal insulation composite system	20	Daylight dimming control system	30
EPS insulation	35–50	PV panels	30
XPS insulation	Building lifetime	Copper (pipe)	75
Cellulose fibre insulation	50	PVC (pipe)	50
Foam glass insulation	Building lifetime	Sewer pipes	75
Stone wool insulation	Building lifetime	Urinals	20
VIP (insulation)	40	Faucets (sink)	20
PUR (insulation)	50	Faucets (shower)	20
Aluminium siding	40	Flush valves (toilet)	20
Opaque modular cladding	30	Flush valves (urinal)	20
Energy efficient windows	20	Toilet fixtures	20
Glazed cladding/Curtain walling	35	Water control sensors	15
Communications installations and controls	15	Water fixtures	50
Lift	30	Water recycle system	30

Source: Alam et al. 2017; Australian Cost Management Manual, Volume 3, p. 52; EATS 2015; Kono et al. 2016; Kubba 2010; Penny 2015; RICS 2018; Tavares, Silva & de Brito 2020

Based on existing retrofitting studies, a 50-year study period is usually assumed in life cycle studies. Jafari, Valentin and Russell (2014) used a 50-year study period to analyse the life cycle cost of retrofitting for sustainable housing. Rodrigues and Freire (2017) also decided to use 50 years as a study period for analysing the environmental impacts on a building envelope by retrofitting. Similarly, Piccardo, Dodoo and Gustavsson (2020) assumed 50 years as the remaining service life of the case building to identify the life cycle carbon balance by improving the insulation performance of the building's envelope. Therefore, if the remaining service life of a retrofitted building cannot be estimated, a 50-year remaining lifetime can be regarded as an acceptable study period for analysing the sustainable performance of retrofitting.

4.3.1.4. Decision rules

Several decision rules are implemented in LCC to test the economic validity of competitive alternatives. Common ones include net present value (NPV), equivalent annual cost (EAC), internal rate of return (IRR), payback period (PBP), and benefit/cost ratio (BCR).

(a) Net present value

Net present value (NPV) is the most frequently used LCC calculation method for assessing an asset's economic viability over its life cycle (Marzouk, Azab & Metawie 2018; Toosi et al. 2020). It is the difference between the discounted revenues and expenses at the expected discount rate (Cotter 2022). It can be calculated based on Equation 4.2 (ISO 2017). NPV is usually calculated to compare different building components with different initial costs and maintenance costs for deciding on investments. The positive result indicates the investment is profitable, and the higher NPV calculated, the more desirable the project. Therefore, the alternative with the highest NPV should be selected to achieve maximised profit (Cotter 2022).

$$NPV = \sum_{n=1}^{p} \frac{C_n}{(1+d)^n} \qquad \text{Equation 4.2.}$$

Where,

NPV – net present value
C_n – the cost in year, n
d – the expected real discount rate per annum
n – the number of years between the base date and the occurrence of the cost
p – the period of analysis

(b) Equivalent annual cost or income

The equivalent annual cost (EAC) can also be used to assess the life cycle economic viability of assets if the residual service life of different existing buildings is uncertain (Rodrigues & Freire 2017). To calculate EAC, different costs over the building's remaining service life can be converted to an equivalent annual amount at the expected discount rate (Rodrigues & Freire 2017). The calculation can be achieved based on Equation 4.3 (ISO 2017). Positive value represents income, and negative value represents cost. The alternative with the lowest annual cost or highest annual income should be selected (Cotter 2022).

$$EAC = \frac{Cd}{(1+d)^n - 1} \qquad \text{Equation 4.3.}$$

Where,

EAC – equivalent annual cost or income
C – the cost in year n
d – the expected real discount rate per annum
n – the number of years between the base date and the occurrence of the cost

EAC is a more suitable LCC technique to calculate a product's life cycle cost when the natural replacement cycle is not an exact multiple of the study period (ISO 2017). Moreover, it is especially meaningful for building owners or investors, since EAC can illustrate whether this project creates enough cash flow to pay back the loan and produce enough after-tax cash flow to reinvest in other future products (Cotter 2022).

(c) Internal rate of return (IRR)

The internal rate of return (IRR) is the compound rate of interest that makes costs equal to benefits when cash flow is reinvested at a given interest rate (ISO 2017). It can be calculated based on Equation 4.4. The alternative that can maximise IRR should be selected (Cotter 2022).

$$NPV\ (cost, r) = NPV(benefit, r) \qquad \text{Equation 4.4.}$$

Where,

NPV – net present value
r – discount rate that makes the NPV equal to zero

IRR is usually used to rank investment sizes of alternatives and associated patterns of cash flow over time, ultimately to decide whether they are acceptable (Cotter 2022; ISO 2017). However, IRR may violate the re-investment assumption and can also have several different outcomes depending on changes of signs of cash flow, such as the extra cost caused by maintenance or refurbishment (Arjunan & Kannapiran 2017; Lohmann 1988).

(d) (Adjusted) Payback period

Payback period (PBP) is the time it takes to cover investment costs (ISO 2017). A simple payback period uses non-discounted values for future money, while an adjusted (discounted) payback period uses the present value (ISO 2017). The alternative with the smallest (adjusted) payback period is desirable (Cotter 2022). The major problem with this decision rule is it ignores the benefits and costs that occur after the end of the payback period (ISO 2017).

(e) Benefit/cost ratio

In contrast to the above-discussed decision rules for measuring profits by an investment, benefit/cost ratio (BCR) is used to measure the profitability per dollar invested of an investment. It can be calculated based on Equation 4.5 (Cotter 2022). A BCR greater than one means the project is profitable, and the bigger the BCR, the more desirable the project.

$$BCR = \frac{\sum_{n=0}^{n} \frac{B_n}{(1+d)^n}}{\sum_{n=0}^{n} \frac{C_n}{(1+d)^n}} \qquad \text{Equation 4.5.}$$

Where,

BCR – benefit/cost ratio
B_n – project benefits during period n
C_n – project costs during period n
n – number of periods
d – discount rate

BCR is regarded as convenient for investors to select the most profitable alternative by ranking the BCR of all potential projects. Therefore, it is commonly used to assess competitive projects' validity and relative merit (Tung 1992).

This study develops a model for deciding retrofitting strategies in which different retrofitting activities are contained. These retrofitting activities are selected to improve the performance of associated building components and systems. According to Table 4.5, typical building materials and building system life expectancy varies from 15 to 50 years. It is difficult to ensure the life expectancy of all upgraded building materials and building systems is an exact multiple of the study period – estimated or assumed remaining service life. Moreover, compared to construction for new buildings, reinvestment and management issues are more associated with retrofitting projects. Therefore, EAC is selected in this study to calculate the life cycle cost of adopted retrofitting activities.

4.3.1.5. Limitations

Even though LCC has been used to assess the economic performance of buildings for decades, there is a certain limitation remaining to be solved – how to treat externalities in LCC (Hunkeler & Rebitzer 2005; Wulf et al. 2019; Zamagni, Pesonen & Swarr 2013). First, it is a major concern to define the scope of LCC. From the perspective of life cycle sustainability, economic, environmental and social conditions evolve over time, and double counting may occur if no clear interface is defined between the three pillars (Hunkeler & Rebitzer 2005). Second, if externalities are included in LCC, the issue of whether environmental and social values should be monetised arises (Wulf et al. 2019). As discussed in Section 4.2.1.2, there is little agreement on attaching monetary value to environmental impact. Moreover, it is also a controversial issue to monetise social value. Therefore, instead of monetising environmental and social values that can be regarded as externalities in LCC, a comprehensive assessment should be conducted by incorporating environmental and social dimensions to track trade-offs between the three pillars from a long-term perspective (Wulf et al. 2019; Zamagni, Pesonen & Swarr 2013).

4.3.2. Cost benefit analysis

Cost benefit analysis (CBA) is a common economic assessment method to assess the attractiveness of projects, from a whole of society perspective (Hoogmartens et al. 2014). It is widely used in decision making by ranking alternatives based on their cost and different benefits (Hoogmartens et al. 2014). The costs and benefits assessed in CBA may not be simply summed up, so conversion fractions are used to convert them to one metric – money (Jeswani et al. 2010).

By monetising costs and benefits, CBA can represent assessment results as a single criterion (money), which enables intuitionistic comparison of different alternatives (Jeswani et al. 2010). However, monetisation is criticised as a simplistic way, which may lead to limitations in applying CBA. First, it is challenging to get consensus on an exact price of damages (Hoogmartens et al. 2014). Second, benefits and costs are monetised in CBA by deterministic values, but the uncertainty of these values is often unknown (Dong et al. 2018). Lastly, as an economic analysis tool, CBA is conducted from a whole of society view by considering external factors. Therefore, it is not suitable to be taken to assess economic performance of a project by only considering effects on the stakeholders (Hoogmartens et al. 2014).

4.4. Social impact assessment

As discussed in Section 3.2.3 of Chapter 3, the social dimension has not received the same attention as environmental and economic dimensions (UNEP/SETAC 2011). It can be seen that environmental and/or economic dimensions are considered in most well-known assessment schemes, but the social dimension is rarely involved (Fatourehchi & Zarghami 2020). There is not an international standard similar to the environmental and economic dimensions which can standardise assessment criteria and assessment methods that is widely accepted. Therefore, the assessment methods for social impact are still limited. Reviewing related studies, two methods are commonly used to assess the social impacts of buildings: the social cost benefit analysis (SCBA) and social life cycle assessment (S-LCA). Apart from these two, a social assessment standard EN16309:2014 was initiated by the European Union (BSI 2014). However, like most other social assessment methods, it mainly relies on qualitative criteria and checklists, leading to less accurate assessments.

4.4.1. Social cost benefit analysis

Social cost benefit analysis (SCBA) is an alternative form of the original CBA, but with social-economic criteria incorporated in the assessment (de Nooij 2011; Dodgson et al. 2009). The investment decision based on pure economic cost analysis may also result in impacts on society such as climate change, traffic congestion, etc. Therefore, SCBA as a socio-economic evaluation method is adopted to support decisions, especially those made by government (Hauck et al. 2016).

Similar to the original CBA, all relevant costs and benefits are also evaluated in SCBA in monetary terms (Dodgson et al. 2009). However, the difference is that the estimated costs and benefits in SCBA can quantify societal differences with and without a project. Moreover, in addition to evaluating impacts on decision makers, externalities are also taken into account in

SCBA (de Nooij 2011). Based on the study by de Nooij (2011), SCBA ought to include investment costs, changes in losses, project risk analysis, potential synergies and interconnections across projects. It can also consider socio-economic factors like the exchange of ancillary services, the benefits of a more integrated market, security of energy supply, and optimisation of energy generation. Due to its ability to evaluate projects with multiple aspects, SCBA has been used to support decision making about infrastructure design, such as bridges, building materials, and road safety improvement (Hauck et al. 2016).

A benefit of SCBA is that all effects are formulated precisely by allocating a price on each assessed impact (de Nooij 2011). However, the monetary-equivalent measure in SCBA also receives many critiques (Dodgson et al. 2009; Fleurbaey & Abi-Rafeh 2020). Some specialists in welfare economics even object to this approach because no weights are introduced in SCBA (Fleurbaey & Abi-Rafeh 2020). They argue that it is difficult to reach a consensus on attaching an exact price to welfare variation (referring to the willingness to pay or willingness to accept) (Fleurbaey & Abi-Rafeh 2020). Indeed, social values tend to change in different situations. For rational estimates, the same values should be used across the board because society needs to ration investments of scarce resources. However, it does not mean those values should be used in other situations, since the willingness to pay or accept changes with different situations.

4.4.2. Social life cycle assessment

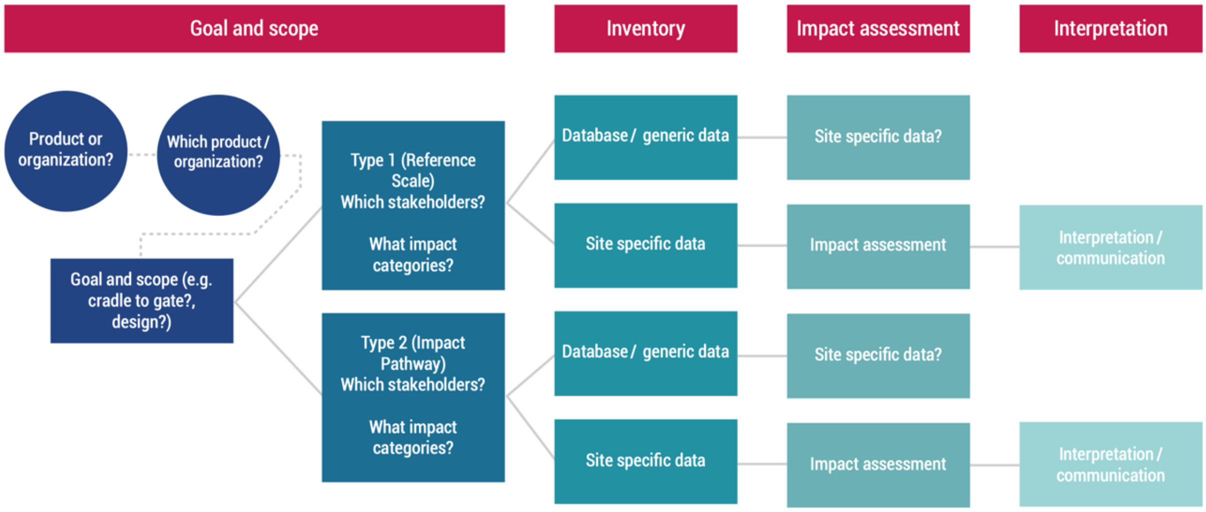
Social life cycle assessment (S-LCA) is a method for assessing positive and negative impacts throughout the product’s life cycle by evaluating its social and socio-economic elements (UNEP/SETAC 2009). Although assessing social impacts by a life cycle approach has been studied since the 1990s, little progress has been made after its initiation, leading to it falling behind the other two life cycle methods – LCA and LCC (Hunkeler & Rebitzer 2005; Klöpffer 2003). The review study by Huertas-Valdivia et al. (2020) analysed publications about S-LCA from 2003 to 2018. The result showed that about 66% of all 187 relevant articles were published, primarily by European authors, after 2009, when the first international S-LCA assessment guideline – UNEP/SETAC Guidelines for Social Life Cycle Assessment of Products – was launched. Additionally, only three articles out of the total analysed articles were about building and construction. The study by Fan et al. (2018) also indicated the first time S-LCA was applied in the area of civil engineering was in 2013. Therefore, even though rapid growth in S-LCA study has occurred in recent years, it is still at an early developing stage (Dong & Ng 2016; Fan et al. 2018; Huertas-Valdivia et al. 2020).

It is undeniable that there is an urgent need for S-LCA. The social life cycle performance should be assessed and optimised in the early stage of a construction project to support decision making (Liu & Qian 2019). Most importantly, there is a need for a life cycle approach for assessing social impacts along with environmental life cycle assessment (ELCA) and environmental life cycle costing (ELCC) to complete a comprehensive sustainability assessment (Benoît et al. 2010; Fan et al. 2018). ELCA and ELCC, and the differences between LCA and ELCA, and between LCC and ELCC, are discussed in Section 4.5.2.

4.4.2.1. The assessment framework

The S-LCA guideline initiated in 2009 explains how the ELCA approach could be adapted to assess the social and socio-economic impacts of products (UNEP/SETAC 2020). The methodological framework of S-LCA is similar to the assessment framework of LCA, consisting of goal and scope, inventory life cycle analysis, impact assessment, and interpretation (UNEP/SETAC 2009). The updated version in 2020 gives a more detailed introduction to each phase, shown in Figures 4.4 and 4.5.

Figure 4.4. S-LCA decision tree



Source: UNEP/SETAC 2020

Figure 4.5. Assessment framework of S-LCA by reference scale approach

Phase 1. Goal and scope	• Identify assessment goal • Define functional unit • Define reference flow • Define product system • Define system boundary • Identify activity variable • Identify cut-off criteria • Identify limitations of data access • Identify stakeholder categorization and involvement • Select impact assessment method and impact subcategories • Identify indicators, data type, and data collection strategies
Phase 2. Life cycle inventory	• Identify the data to be prioritised for collection • Collect data for hotpots assessment if this is part of the Goal and Scope • Collect data for the selected/relevant stakeholders and subcategories • Collect complementary data for the impact assessment • Collect site specific (primary) and generic (secondary) data for unit process and activity variables • Collect data for scoring and/or weighting
Phase 3. Impact assessment	• Establish reference scales for impact assessment • Data collection • Assess data against the reference scale • Apply an impact assessment method to group by subcategory or impact category and aggregate results over the value chain using an activity variable • Finally weight results • Present the results
Phase 4. Interpretation	• Completeness check • Consistency check • Sensitivity and data quality check • Materiality assessment • Conclusions, limitations, and recommendations

Source: UNEP/SETAC 2020

The first phase is similar to LCA in that the assessment goal and scope should be identified first. As Figure 4.4 shows, whether the assessment will focus on a product or an organisation needs to be clarified. Following that, the study scope should be defined, including system boundary, functional unit, product system, cut-off criteria, etc. (as Figure 4.5 shows). In S-LCA, two main impact assessment approaches are highlighted, and need be clarified in this phase (UNEP/SETAC 2020):

(1) Reference Scale Approach (Type I): the assessment aim is to describe a product system with an emphasis on social performance and social risk.

(2) Impact Pathway Approach (Type II): the assessment aim is to predict the effects of the product system with an emphasis on identifying potential social impacts.

By applying the Reference Scale Approach, the performance reference points (PRPs) that are specific referent points of expected activity need to be identified. They are used as a reference to assess the social performance of these activities of organisations in the product system. Therefore, the assessment mainly relies on data, information or judgment. It is normally conducted to assess the immediate effect of evaluated activities and the magnitude and significance of potential further social impacts (UNEP/SETAC 2020).

The Impact Pathway Approach is more in line with E-LCA, in which impacts are assessed based on a “characterisation” process of analysing causal or correlation/regression-based directional relationships between the product system/organisations’ activities and the subsequent potential social impacts. Therefore, the assessment is normally used to identify and track the effects of possible activities on longer-term ramifications along an impact pathway (UNEP/SETAC 2020).

In this study, social impact assessment is adopted mainly for assessing the magnitude and significance of the immediate social impacts (in the construction stage) and potential social impacts further down the line (in the operation stage) by retrofitting activities. The cause-and-effect relationship between activities and the associated social consequence is not the focus of this study. Therefore, the Reference Scale Approach (Type I) is more suitable and is applied in this study.

Following the goal and scope definition, the next phase is inventory analysis, where a data collection strategy needs to be developed and decided, in particular, whether to use an S-LCA database or other data resources, and whether to collect site-specific data (UNEP/SETAC 2020).

The third phase is to conduct impact assessment. Since the Reference Scale Approach is adopted in this study, Phase 3 in Figure 4.5 lists the steps of implementing the Reference Scale Approach. The first step is establishing the performance reference points. The second step is collecting required data. The third step is assessing the data against the reference scale. The fourth step is applying a specific assessment method to group impacts based on impact (sub)categories, in which the assessment results can be aggregated. In the final step, the weighted results can be obtained (UNEP/SETAC 2020).

The last phase is to interpret the assessment results built according to ISO 14044 (ISO 2006b). First, the whole assessment process should be reviewed. Then, checks for completeness, consistency, sensitivity and data quality, and materiality assessment need be conducted. Based on the review and check results, the assessment process can be interpreted by summarising results, summarising limitations, and providing recommendations (UNEP/SETAC 2020).

4.4.2.2. Limitations

Two publications by UNEP/SETAC (2020) provide a conceptual framework of social life cycle impact assessment, which guide practitioners and researchers to assess positive and negative social impacts of products or organisations. However, two main limitations of S-LCA remain to be solved.

First, there is no consensus on the social life cycle impact assessment method regulated in S-LCA (Fan et al. 2018). Researchers have to design the assessment method by selecting the specific scoring system, weighting methods, and even stakeholders. Therefore, different assessment results may be achieved in the same study by different researchers.

The second limitation of S-LCA is the lack of consensus on assessment indicators (Huertas-Valdivia et al. 2020). Assessment indicators play a crucial role in S-LCA for providing short- and long-term information, which can help organisations better comprehend their current situation and development tendencies (Kühnen & Hahn 2017). However, the S-LCA assessment framework by UNEP/SETAC does not provide social indicators that can be directly attributed to products or processes. As a result, researchers must use indicators from a different reference level (organisations, regions), and the product relation must then be made based on appropriate methodological assumptions (Finkbeiner et al. 2010).

Regarding these two limitations of S-LCA, even though the Reference Scale Approach is used in this study, the rating scale, assessment method, weighting method, and assessment indicators have to be customised according to the specific situation of this study.

It must be noted that, in contrast to SCBA where social impacts are quantified by discounting monetised values, value scores decided based on judgment of social impacts are used as proxy variables in S-LCA. However, how to time-discount impacts judged by subjective information is still an unsolved problem. Moreover, if converting judgment into a monetary scale similar to SCBA, the same critique of monetising social value would apply. Therefore, in this study, social impacts are not discounted, and it is assumed that the social impacts would be constant in the remaining service life of the building.

4.5. Multi-dimensional sustainability model

Assessment methods of sustainable development in a single dimension are available. However, sustainable development requires integration and balanced environmental, economic and social development (as defined in Section 2.4 of Chapter 2). For a long time, researchers have made efforts to amalgamate the environmental, economic and social dimensions to support decision making of sustainable designs. As discussed in Section 4.4, the social dimension is the least developed pillar among the three pillars. Therefore, the two-pillar model combining the environmental and economic dimensions is commonly implemented to assess sustainability performance and support decision making. This section discusses the two-pillar model and three-pillar model of sustainability assessment and multi-criteria decision making (MCDM).

4.5.1. Integrate two pillars into sustainability assessment

Since the concept of sustainable development is implemented in the construction and property sector, the concept of “cost-optimality” is regarded as the drive for designing new buildings and retrofitting existing buildings (Ascione et al. 2017). Energy efficiency and costs are the main indicators used for comparison during the multi-stage optimisation process due to the common application in other studies (Ascione et al. 2017).

Many studies have integrated LCA and LCC to evaluate buildings’ performance (Fouche & Crawford 2017). Based on the study by Miah, Koh and Stone (2017), there are six types of LCA–LCC integration, which can be categorised into three groups based on integration approaches: conducting LCA and LCC on the same product or services, but showing assessment results separately; using LCA and LCC as two criteria to evaluate decision-making options, and aggregating LCA and LCC assessments based on the mechanism of decision making; and expanding existing LCC to include LCA.

The first integration approach is to conduct LCA and LCC on the same product or service but show the assessment results of LCA and LCC separately. Therefore, a portfolio of results is represented as tables, bar graphs, etc. in this integration category (Miah, Koh & Stone 2017). This integration method was adopted in the study by Pombo, Rivela and Neila (2016), which compared the sustainability performance of common renovation strategies. In their study, the LCA results and LCC results of selected renovation strategies were presented in two separate tables, and according to these results, they were ranked for environmental performance and economic performance respectively.

The second integration category regards LCA and LCC as two assessment criteria in a decision-making process. The LCA and LCC results can be aggregated based on the mechanism of the decision-making method, such as optimisation in multi-criteria decision making (MADM) (Miah, Koh & Stone 2017). In 1994, a project named “the Building for Environmental and Economic Sustainability” (BEES) was initiated by the US National Institute of Standards and Technology (NIST) for selecting environmentally and economically balanced building products (Alamu et al. 2021; Lippiatt 1998; Xu et al. 2022). In BEES, LCA and LCC work as the assessment baseline, and the LCA and LCC results are aggregated as one based on the decision-making mechanism of multi-attribute decision analysis to select the “most” sustainable product (NIST 2020).

The last integration category is expanding the existing LCC to include LCA (Miah, Koh & Stone 2017; Zuo et al. 2017). One method is to give a monetary value to external environmental impacts (Zuo et al. 2017). The study by Kneifel (2010) monetises the CO_2 emissions of a building and includes the value in LCC to evaluate the building’s economic performance by considering the external environmental impact (CO_2 emissions). Environmental life cycle costing (ELCC) is another example to include environmental impacts in LCC (Miah, Koh & Stone 2017; Zuo et al. 2017). Compared to traditional LCC, the assessment aim, perspective and scope in ELCC are much closer to those in LCA. Therefore, it is fully compatible and always conducted with LCA (Miah, Koh & Stone 2017; Zuo et al. 2017). Moreover, ELCC is one pillar in life cycle sustainability assessment (LCSA), which is discussed in Section 4.5.2.

Similarly, CBA can also be integrated with LCA. It can be realised by conducting LCA and CBA in parallel to evaluate economic and environmental performance of a product or service (Dong et al. 2018). Alternatively, the CBA can be expanded to include LCA by monetising external environmental impacts – environmental cost benefit analysis (ECBA) (Dong et al. 2018; Hoogmartens et al. 2014). The study by Manzo and Salling (2016) assessed the environmental and economic impacts of vehicles by including monetised air pollution into CBA. The result showed that the indirect environmental effects account for a significant portion of the project's estimated expenditure.

4.5.2. Life cycle sustainability assessment

With the wide recognition of the concept of sustainability development, the demand to integrate social and economic dimensions of sustainability into LCA has become increasingly strong. As discussed above, many assessment frameworks can incorporate environmental and economic dimensions, but the social dimension is absent. In 2003, the social dimension (S-LCA) was first integrated with LCA and LCC by Klöpffer (2003). Then, the formation and integration of all the three pillars was proposed and discussed by Hunkeler and Rebitzer (2005) as life cycle sustainability assessment (LCSA).

LCSA is a three-pillar model built on the principle of triple-bottom line (Kloepffer 2008; Llatas, Soust-Verdaguer & Passer 2020; Moslehi & Reddy 2019). With the three pillars included, LCSA provides a complete view of the positive and negative impacts along the product's life cycle. In addition, LCSA also supports decision making by prioritising resources and investing them where there are more opportunities for positive impacts and fewer negative ones (Ciroth et al. 2011).

In LCSA, environmental impact is assessed using environmental LCA (ELCA), the economic dimension is assessed using environmental life cycle costing (ELCC), and social life cycle assessment (S-LCA) is used to assess social impacts. These three techniques have the same methodology based on the standard ISO 14040 (ISO 2006a), and assessment results for each method are used to represent the performance of life cycle sustainability, as Equation 4.6 shows (Llatas, Soust-Verdaguer & Passer 2020; Soust-Verdaguer et al. 2022).

$$\text{LCSA} = \text{ELCA} + \text{ELCC} + \text{S-LCA} \qquad \text{Equation 4.6.}$$

Where,

LCSA – life cycle sustainability assessment
ELCA – environmental life cycle assessment
ELCC – environmental life cycle costing
S-LCA – social life cycle assessment

As discussed in Section 4.2.1, LCA is the only environmental impact assessment method with a standardised assessment framework (see Section 4.2.1). It is also used to assess environmental impacts throughout a product's life cycle in LCSA. ELCC is adopted to evaluate the performance in the economic dimension. The concept of ELCC was initiated by Hunkeler, Lichtenvort and Rebitzer (2008). The UNEP report about LCSA identifies three types of LCC with different boundaries of analysis: conventional LCC, where the post-production stages are overlooked; ELCC, which is a mirror of LCA and considers all costs associated with the life cycle of a product that are directly covered by any one or more of the actors (stakeholders) in the product's life cycle; and social LCC where all external and private costs and benefits are monetised (Ciroth et al. 2011; Fauzi et al. 2019). It has generally been accepted that ELCC should be used in LCSA because it complies with the concept of LCA and is consistent with the environmental dimension for avoiding double-counting (Finkbeiner et al. 2010). S-LCA is the third pillar in LCSA to assess a product's or organisation's social impacts (see Section 4.4.2).

With the three pillars integrated, LCSA is believed to be a comprehensive method that can draw a whole picture of sustainability assessment, and it is becoming increasingly significant (Toosi et al. 2020). However, certain limitations of LCSA are identified and urgently need to be solved. First, compared to the other two techniques, S-LCA is still weak and uncommon, leading to the social pillar being left out of consideration in many studies (Ostermeyer, Wallbaum & Reuter 2013; Toosi et al. 2020; Vilches, Garcia-Martinez & Sanchez-Montañes 2017; Zamagni, Pesonen & Swarr 2013). Second, LCSA models each pillar of sustainability independently, and each pillar's assessment results are combined in a final step of decision analysis. Even though this assessment mechanism can emphasise the sustainability view for each pillar, it hinders a comprehensive knowledge of the system due to the neglect of considering trade-offs between the three sustainability pillars (Zamagni, Pesonen & Swarr 2013). As a result, ELCA, ELCC and S-LCA do not facilitate the decision-making process unless they are amalgamated into a decision-making support system (Toosi et al. 2020).

4.5.3. Muti-criteria decision making

Decision making is a complex and challenging task in most decision-making processes where multiple, even conflicting, objectives need to be considered. Moreover, uncertainty from different sources, such as subjective opinions from decision makers and changing demands of stakeholders, adds complexity (Mohammad 2021). This is why multi-criteria decision making (MCDM) is preferred over one-dimensional decision making, which can only consider single criterion (Ekel, Pedrycz & Pereira Jr 2020; Geneletti 2019). Moreover, MCDM can deal with subjective components of the decision-making process, which are always ignored by the one-dimensional model (Munier, Hontoria & Jiménez-Sáez 2019).

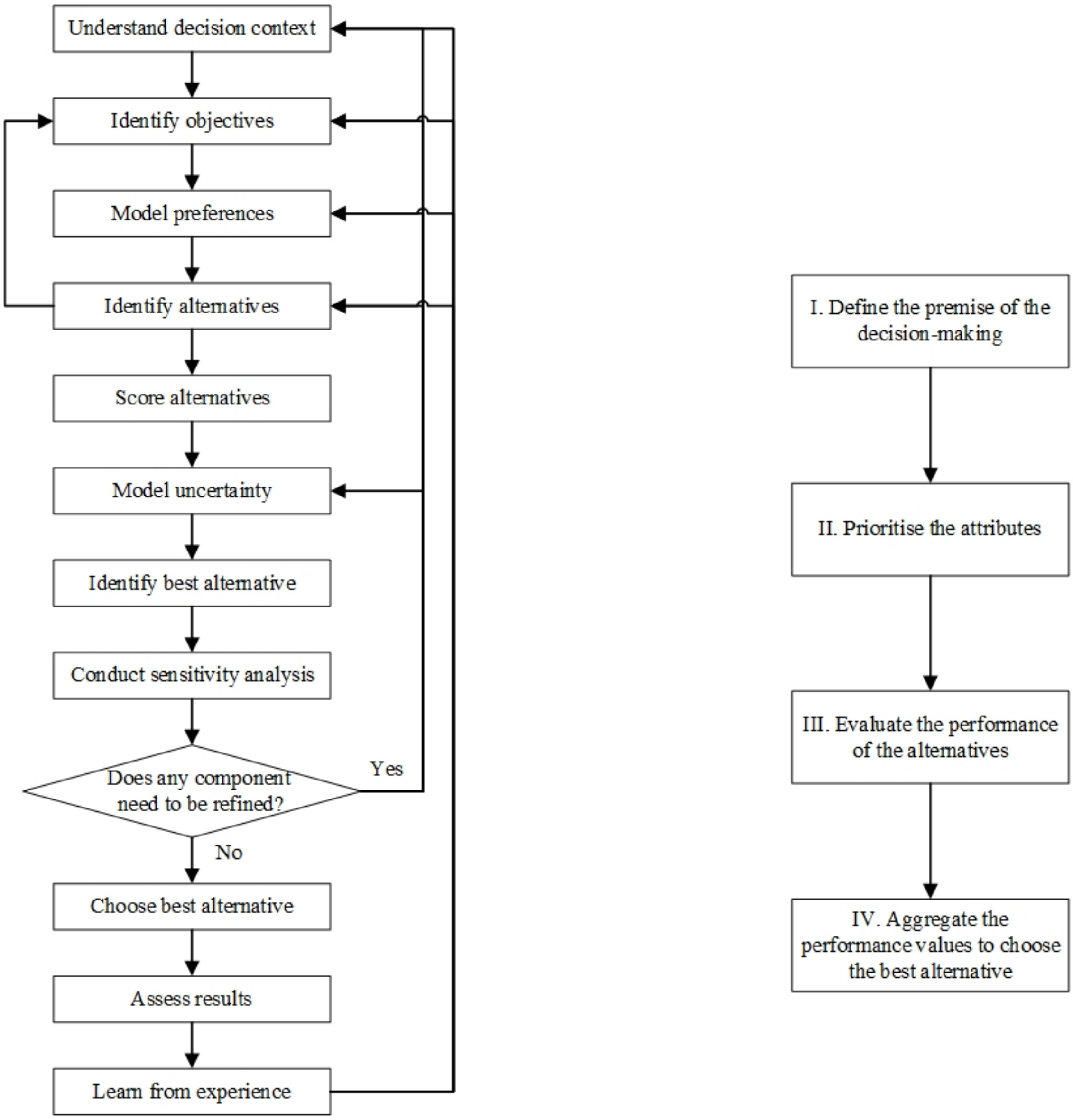
Munier, Hontoria and Jiménez-Sáez (2019, p. 5) defined MCDM as “a process of selecting one of the several courses of action, alternatives or options, which must simultaneously satisfy many different conflicting and even contradictory criteria”. The essence of MCDM is to explore balance or trade-offs between the benefits and drawbacks of different alternatives by illustrating their performance across all criteria (Geneletti 2019). After all, compared to finding the best solution which is almost impossible in reality, reaching a consensus or compromise amongst all the involved parties is more preferred (Munier, Hontoria & Jiménez-Sáez 2019). Furthermore, with the capability to deal with group decisions, MCDM can identify similarities or potential areas of conflicts amongst stakeholders. Eventually, it can contribute to a more comprehensive understanding of the values held by others (Kiker et al. 2005).

Based on formulated decision problems, MCDM is categorised into two types: multi-objective decision making (MODM) and multi-attribute decision making (MADM). Table 4.6 summarises their characteristics and application. The typical steps in MODM and MADM are illustrated in Figure 4.6 (a) and (b), respectively.

Table 4.6. Characteristics of MODM and MADM

		MODM	**MADM**
Similarity		• Multiple criteria: each problem has multiple criteria • Conflict criteria: multiple criteria conflict with each other • Incommensurable units: criteria may be measured in different units	
Difference	Type of model	A design model for designing the optimal solution	A selecting model for selecting the best from a pool of predetermined alternatives
	Decision types	Decisions are taken via several objectives in a continuous decision space	Decisions are made based on preferences with discrete decision spaces
	Alternatives	• No predetermined alternatives are needed • Infinite alternatives can be dealt with	• Predetermined alternatives are needed • Limited, finite alternatives can be dealt with
	Mechanism of decision making	Maximising or minimising objective functions which describe objectives and constraints of the multi-objective decision problems	A systematic method with which a discrete performance rating mechanism is integrated to evaluate and compare the performance of these predetermined alternatives
	Fields of application	Mainly in the field of operational research and management science	Different fields, but mainly for solving management and evaluation decision-making problems
Benefits		• Promotes clear thinking • Provides comprehension and insight • Explains decision rationale • Enables communication and understanding among multiple stakeholders • Deals with conflicting, even commensurable objectives	• Copes with conflicting, even commensurable objectives • Is more relevant and significant for dealing with real-world decision problems
Limits		Decision making is constrained by information availability and domain knowledge	
		Since infinite alternatives can be considered, it is a constant challenge for decision makers to select the best materials and constructions to satisfy complex design problems.	The decision results largely depend on the quality of predetermined items
Sources		Asmone & Chew 2018; Alinezhad & Khalili 2019; Brownley 2013; Ekel, Pedrycz & Pereira Jr 2020; Jones & Tamiz 2010; Zavadskas, Turskis & Kildiene 2014	Asmone & Chew 2018; Alinezhad & Khalili 2019; Ekel, Pedrycz & Pereira Jr 2020; Yu, Fei & Li 2018; Zavadskas, Turskis & Kildiene 2014; Zolghadr-Asli et al. 2021

Figure 4.6. Basic steps in MODM and MADM



(a) MODM (Source: Brownley 2013)

(b) MADM (Source: Zolghadr-Asli et al. 2021)

Decision making in sustainable projects is complex and sometimes even difficult to control for the inherent trade-offs between the three sustainability dimensions. Clearly understanding and effectively managing the trade-offs is key to achieving comprehensive sustainability (Kiker et al. 2005). Kiker et al. (2005) further stated that sustainable decisions always involve multiple facets with different priorities and objectives. A sustainable decision is typically based on support from diverse areas of expertise with consideration of different perspectives that represent the requirements of different stakeholders (Ekel, Pedrycz & Pereira Jr 2020; Kiker et al. 2005).

By applying MCDM to retrofitting projects to decide on sustainable retrofitting strategies, two approaches are available: maximum performance, where the retrofitting strategy with the best performance is selected by assessing only one indicator or one dimension of sustainability thus weighting is not necessary; and optimal performance, where the retrofitting strategy with the highest overall performance across a number of indicators or dimensions of sustainability is selected. Thus, weighting needs to be considered (Ostermeyer, Wallbaum & Reuter 2013).

As previously stated, sustainable development requires integration and balanced environmental, economic and social development. In addition, for retrofitting projects, the retrofitting options for the site might be measured against each other instead of reaching hard targets, which allows achieving optimal solutions within project constraints instead of reaching a certain goal (Ostermeyer, Wallbaum & Reuter 2013), such as achieving a certain level of environmental performance improvement regardless of cost. Therefore, the optimal solution (or saying as good as possible) is more desired for retrofitting projects (Ostermeyer, Wallbaum & Reuter 2013). Due to the nature of retrofitting projects, the possibilities for the site should be compared to one another rather than to strict goals. The optimisation model is more suitable for generating retrofitting strategies since it can provide the best overall and balanced performance regarding the three sustainability pillars. Therefore, compared to MADM, MODM is a more suitable decision-making methodology for this study for the ability to generate an optimal solution within project constraints. In addition, it enables dealing with conflicting, even non-commensurable issues by creating a vector based on the assessment criteria relating to the decision, objective functions, and problem constraints (Asmone & Chew 2018).

4.6. Summary

This chapter discussed common assessment methods in each sustainability dimension regarding the assessment framework and their benefits and limitations. LCA and green building rating systems are two common methods to assess environmental impact. For the economic dimension, LCC and CBA are widely used to evaluate income and costs throughout a product's life cycle. SCBA and S-LCA are two methods that can be adopted to assess social impact. Compared to assessment considering only one sustainability dimension, methods that can include two or more dimensions are more able to achieve comprehensive sustainability. The two-pillar model refers to assessment frameworks integrating environmental and economic dimensions to assess sustainability performance and support decision making.

Based on the requirement of sustainable development, the environmental, economic and social dimensions should be integrated in a balanced way. LCSA is an assessment framework that can include the three dimensions to support decision making. In LCSA, ELCA is used to assess environmental impact; ELCC is used to assess life cycle costs; and S-LCA is used to assess social impact. The assessment results of these three assessment techniques are then aggregated by integrating them in a decision-making process. Therefore, even though the three sustainability pillars are covered in LCSA, their mutual relations are neglected in this method. To solve this problem, MCDM is suggested to solve complicated problems with multiple, even conflicting objectives. More importantly, MCDM is an effective method to analyse and balance trade-offs between different assessment criteria. MODM and MADM are two categories under MCDM. MODM can generate optimal solutions within project constraints, while MADM is usually used to select the “best” solution from a pool of predetermined alternatives. Due to the nature of retrofitting projects, the possibilities for the site should be compared to one another rather than to strict goals. The optimisation model is more suitable for generating retrofitting strategies since it can provide the best overall and balanced performance regarding the three sustainability pillars. Therefore, MODM is adopted in this study to build the conceptual model for deciding on retrofitting strategies.

In summary, Chapters 2 to 4 present the literature review about sustainability, retrofitting, and assessment tools of sustainability. Based on the review, a conceptual model for deciding retrofitting strategies for office buildings is developed. The details of the conceptual model are presented in Chapter 6. The next chapter illustrates the research methodology on how the model is developed and how this study is conducted.

Chapter 5. Research methodology

5.1. Introduction

In the previous chapters, existing studies about sustainable development, sustainable retrofitting, and sustainability assessment methods were reviewed. Based on the literature review, it can be concluded that existing buildings are imposing massive negative impacts on the natural environment. Retrofitting is recognised as an effective strategy to alleviate those negative impacts. To attain comprehensive sustainable development, the economic and social dimensions should be integrated with the environmental dimension, and these three dimensions need to be balanced. Therefore, a complete assessment of sustainability needs to be conducted, in which the life cycle impacts in the three dimensions are integrated to evaluate the performance of potential retrofitting activities. Based on the literature review, this study aims to develop a model for deciding retrofitting strategies for office buildings.

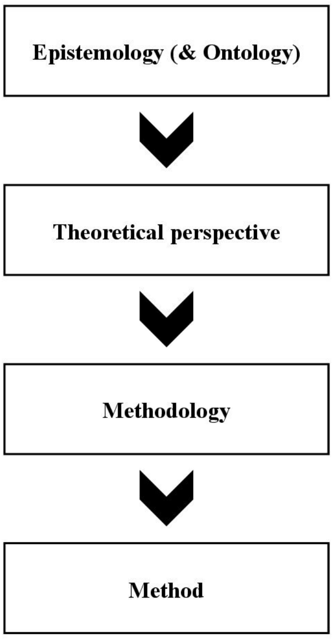
Before presenting the details about how the conceptual model is developed, this chapter first gives an overview of how the research is conducted – the research methodology. Common types of epistemology, theoretical perspectives, methodology, and data collection methods are introduced. Based on discussions of benefits, limits and applicability, suitable ones are selected for this study.

In the beginning of the research, a research proposition is stated based on the generally accepted theory that humans contribute to climate change and the corollary that we can reduce the pressure on the climate by changing the way we interact with the environment. The proposition investigated here is that it is possible to improve sustainability, which could potentially be sufficient to create room for economic growth and improved social wellbeing, by retrofitting existing buildings; and that this can be done by using the triple-bottom line approach. A process from conceptualisation to operationalisation is conducted to test the proposition, and a positivist data collection strategy is employed to realise this process. First, a conceptual model, a fuzzy expression of the research proposition, is developed. This conceptual model can then be converted into an operating model by specifying retrofitting activities and assessment criteria. A case study is conducted to demonstrate how this can be done. In this way, the conceptual model is verified, and the process of using the conceptual model to develop retrofitting strategies can also be illustrated. As a result, the research proposition can be tested, indicating whether the research is valid.

5.2. The research process

Crotty (1998) described the research process as “scaffolded learning”, which can establish structured frameworks for the long-term purpose of researching or learning. The research process consists of four components: epistemology, theoretical perspective, methodology and research methods (Figure 5.1). Combining the explanations from Crotty (1998) and Scotland (2012), the meaning of these four components can be described as follows: epistemology is considered a set of philosophical assumptions about the nature of knowledge. The theoretical perspective is the philosophical stance behind the adopted methodology, which provides theoretical support for the process and grounding its logic and criteria. The methodology is the strategy or plan to rationalise the held research assumptions and link the research actions to the desired outcomes. Research methods refer to a series of techniques or procedures used to collect and analyse the research process. The relationship among these four elements is illustrated in Figure 5.1 and Table 5.1.

Figure 5.1. Basic elements of research process



Source: Crotty 1998

Table 5.1. Relationship among the four elements of the research process

Epistemology	Theoretical perspective	Methodology	Method
• Objectivism • Constructionism • Subjectivism	• Positivism (and post-positivism) • Non-positivism ▪ Interpretivism - Symbolic interactionism - Phenomenology - Hermeneutics - Naturalistic inquiry - Interpretive communities - Critical theory/Critical race theory - Postmodernism - Feminism • Pragmatism Etc.	• Experimental research • Survey research • Ethnography • Phenomenological research • Grounded theory • Heuristic inquiry • Action research • Correlation analysis • Narrative enquiry • Cause-comparative study • Discourse analysis Etc.	• Sampling • Measurement and scaling • Questionnaire • Observation ▪ Participant ▪ Non-participant • Interview • Focus group discussion • Case study • Content analysis • Documents • Audio-visual materials • Statistical analysis Etc.

Source: Crotty 1998

5.2.1. Epistemology and ontology

Epistemology is about how people understand things and what people can consider acceptable knowledge in a discipline (Walliman 2016). It is inherent in the theoretical perspective, and the methodology researchers have applied. Maynard and June (1994, p. 10) further explained, “Epistemology is concerned with providing a philosophical grounding for deciding what kinds of knowledge are possible and how we can ensure that they are both adequate and legitimate”.

Often merging with epistemology, ontology is the study of being. If epistemology deals with how we know what we know, ontology is concerned with “what is” (Crotty 1998). Therefore, ontology is described as the theory of social entities, which is about what exists to be investigated (Walliman 2016). In the research literature, ontology and epistemology are generally discussed together to inform the theoretical perspectives. When discussing the construction of meaningful reality, we cannot avoid talking about the construction of meaning. Nowadays, the term “ontology” is seldom mentioned unless the matter of “being” (radical ontology) needs to be strictly dealt with (Crotty 1998).

There are three main stances to epistemology: objectivism, subjectivism and constructionism (Crotty 1998; Gray 2014).

5.2.1.1. Objectivism

Objectivism takes meanings, and therefore meaningful reality, as an existence that is independent of the operation of any consciousness. In the view of objectivism, the objective truth can always be identified if the researcher goes about it in the right way, regardless of who the researcher is (Crotty 1998; Walliman 2016).

5.2.1.2. Subjectivism

Subjectivism still believes in an external and measurable social reality but emphasises the mediation by people's perceptions which gives meaning to the reality (Curtis & Curtis 2011). Crotty (1998) explains that there is an object (reality) in the view of subjectivism, but it contributes nothing to the generation of meaning.

5.2.1.3. Constructionism

Constructionism refuses to take social reality as an independent phenomenon. Instead, it believes that meaning cannot be discovered but only constructed. It states that meaning can be built in many ways based on different modes of consciousness, and it comes out of an interaction between object and subject to which it is ascribed (Crotty 1998; Curtis & Curtis 2011; Walliman 2016).

The three stances of epistemology help researchers express how they understand what they know or how people look at the world. In this study, the stance of objectivism is taken to reach the research aim: to develop a model for deciding retrofitting strategies to improve the sustainability of existing buildings. Objectivism is chosen because the reality that the sustainable performance of existing buildings can be enhanced by carrying out suitable retrofitting strategies is not affected by who the researcher is or who the people involved in the process are. Moreover, developing suitable retrofitting strategies using the developed model is based on numerical data and calculation, which can be considered objective information.

5.2.2. Theoretical perspectives

The theoretical perspective is concerned with the philosophical attitude embedded in the chosen methodology. To ensure which theoretical perspective should be picked for research, it needs to be clear how the theoretical perspective provides a context for the whole research process and how it works to ground its logic and criteria. Inevitably, the researcher needs to clarify the philosophical assumptions that are stated and brought to the chosen methodology (Crotty 1998). According to the study by Burrell and Morgan (1979), there are four assumptions for social research: (1) ontological assumption, about the nature of reality; (2) epistemological assumption, about the nature of the specific form of knowledge; (3) agency assumption, about the nature of human beings; and (4) methodological assumption, about the process of accessing the knowledge. These assumptions reflect the specific stance or worldview when choosing the particular research methodology and methods. Two main types of theoretical perspectives are highlighted: positivism and non-positivism (Creswell & Poth 2018; Crotty 1998; Gray 2014; Walliman 2016). It is noteworthy here, at the level of theoretical perspectives, the expression of positivism and non-positivism is not a matter of quantitative against qualitative research methods. The quantitative methods can still be adopted in non-positivism research, and vice versa (Crotty 1998).

5.2.2.1. Positivism and Post-positivism

Positivists are those who take a scientific approach to research (Creswell & Poth 2018). It is an objective approach with the elements of being logical and reductionistic and emphasising an empirical process of data collection. Eventually, the relationship between causes and effects can be established (Creswell & Poth 2018; Walliman 2016). It is a process of accumulating facts about the world, and the generated causes and effects are regarded as a scientific theory (Gray 2014). Positivism has the greatest confidence in science since positivists believe that scientific knowledge is certain and accurate. Scientific knowledge is sharply opposed to the information from opinions, feelings, beliefs and assumptions gained by non-scientific approaches (Crotty 1998). For this reason, positivism ignores issues like power, subjectivity, and cultural relativism etc., because the reliability and validity of their data are hardly tested judging by a positivistic measure (Curtis & Curtis 2011). The theoretical perspective of positivism can be adopted in various kinds of studies, such as grounded theory, phenomenology and other analysis strategies (Creswell & Poth 2018). In general, positivism holds three arguments (Gray 2014):

- What can be verified by our sensations or calculation constitutes the reality.
- Scientific observation (as opposed to philosophical speculation) is the primary inquiry method.
- Both natural and human sciences share common logical and methodological principles that deal with facts and not with values.

However, it is noted that there is a difference between what positivists are supposed to do and what actually has been done because many so-called "facts" that serve as the components of scientific theories are not directly observed at all (Crotty 1998). As a result, uncertainty may be caused by holding a positivism theoretical perspective. For this reason, instead of passively noting theories found in nature, post-positivism claims to actively construct scientific knowledge (Creswell & Poth 2018; Crotty 1998).

5.2.2.2. Non-positivism – Interpretivism

There are two main anti-positivist stances: interpretivism and pragmatism. Interpretivism is a major anti-positivist stance which recognises the significance of subjective meanings in social reality (Walliman 2016). It is a process of looking for the culturally traced and historically situated interpretations of the world (Crotty 1998; Gray 2014). Gray (2014) further elaborates on this by saying that, in the view of interpretivism, the direct relationship between ourselves (subjects) and the world (object) does not exist, and the world can only be interpreted through classification schemas existing only in our minds. There are four common interpretive approaches: symbolic interactionism, phenomenology, hermeneutics, and naturalistic inquiry. The epistemology can be closely linked to constructionism (Gray 2014). If the process, however, is recognised to be influenced by researchers, and the aim of the research is to understand the deep structure of the phenomenon or to understand the phenomenon via the meaning that the insiders assign to it, interpretivism is more appropriate than subjectivism (Burrell & Morgan 1979; Crotty 1998). There are a few additional non-positivism stances, including critical theory/critical race theory, postmodernism, and feminism (Crotty 1998; Gray 2014). All these stances can be categorised in the field of interpretivism because this research attempts to interpret communities' stances, which is why Creswell and Poth (2018) named this type of interpretivism interpretive communities.

5.2.2.3. Non-positivism – Pragmatism

Pragmatism holds a kind of worldview that focuses on the research outcomes and solutions to problems rather than antecedent conditions (Creswell & Poth 2018). Therefore, there is no particular type of method assigned. Methods are suitable and effective as long as their application "works". The direction for the basic ideas can be summarised as (Cherryholmes 1992; Murphy 1990):

- Pragmatism is not committed to any system of philosophy and reality.
- Individual researchers have the freedom to choose any research procedures, methods and techniques as they best meet their requirements and purposes.
- Pragmatists do not see the world in a purely quantitative or qualitative way. Both quantitative and qualitative methods can be used to collect and analyse data.
- Pragmatists agree that research occurs from time to time in social, historical, political and other contexts.
- Pragmatists look for "what" and "how" to research based on the pursued research outcomes.

In practice, multiple data collection methods (quantitative and qualitative) are employed to best answer research questions. Again, pragmatism emphasises the importance of conducting research to best address the research problems (Creswell & Poth 2018).

In this study, the theoretical perspective of positivism is held to develop the conceptual model because the whole process of model development is objective. It deals with the fact that conducting suitable retrofitting strategies can improve the sustainable performance of existing office buildings. It will not change with the different opinions of different people.

5.2.3. Research methodology

Research methodology refers to tasks, strategies and criteria that shape the scientific inquiry, including all aspects of a research process (Gerring 2011). As discussed above, there are different theoretical perspectives; thus, various methodologies are needed to deal with different kinds of problems and seek different types of answers. Quantitative and qualitative methodologies are the two major categories implemented in social science (Cresswell 2012; Fellows & Liu 2015; Taylor, Bogdan & DeVault 2015). Quantitative methodologies put considerable trust in numerical data; in contrast, qualitative methodologies attempt to use words and observations to describe reality (Amaratunga et al. 2002). Even though there is a clear difference between these two methodologies, qualitative and quantitative methods are not mutually exclusive, and both can be used jointly to address research problems (Hughes 2012; Taylor, Bogdan & DeVault 2015).

5.2.3.1. Quantitative methodology

A quantitative methodology is regarded as an objective research approach. It is used to study the current circumstances of people and events with concern for amounts and frequencies (Thomas 2003). Quantitative studies usually collect data as numbers that can be used to build a systematically organised set of materials for either testing or generating hypotheses (Olsen 2012). This study discusses four types of quantitative methods: survey, correlation analysis, causal-comparative study, and experiment (Creswell 2003; Mertler 2018; Thomas 2003). These four methods can generate numerical results that allow researchers to draw a precise difference between members of a group and between groups as units (Thomas 2003). The advantages and limitations of these four methods are listed in Table 5.2.

Table 5.2. Summary of advantages and limitations of four quantitative methods

Type of method	Description	Advantages	Limitations
Survey research	Survey methods involve gathering information about the current status of some target variables within a particular collectivity and then summarising the findings.	• Surveys are most helpful in revealing the current status of a target variable within a particular entity. • The accuracy of description is enhanced if the status of variables is cast in numerical form than if the results are reported using imprecise verbal expressions such as many, a few, or significantly more.	It fails to show the unique way that the target variable fits into the pattern of the individual units within the collectivity.
Correlation analysis	Correlation studies are designed to answer the general question: What happens to one variable when another variable changes? Descriptions of the relationship between variables can range in precision from very general verbal observations to highly specific statistical amounts.	Using statistical techniques to calculate the degree of relationship between phenomena can provide more precise information than estimates of relationships cast in phrases such as "not much of a connection among".	Many of the phenomena that researchers investigate do not lend themselves to precise quantification.
Causal-comparative study	Causal-comparative study is for exploring the reasons behind existing differences between two or more groups.	It is an effective alternative to experimental designs, particularly when the independent/grouping variables cannot or should not be manipulated.	Because the cause under investigation has already occurred, the researcher has no control over it, which is incredibly limiting when researchers are trying to conclude cause-and-effect relationships.
Experimental research	An experiment consists of treating objects in a defined way and then evaluating the outcome to determine how the treatment influenced the objects and why the treatment had such an effect.	Experiments provide information about the apparent causes of changes in characteristics.	The requirements for designing and conducting true experimental studies are extremely stringent and, in some cases, prohibitive. Researchers must also go to great lengths to ensure that their designs, data and conclusions are not subject to a variety of threats to validity.

Source: Adapted from Creswell 2003; Mertler 2018

Quantitative research methodology is an effective way to gain information about selected features of either a population's members or the whole population. The numerical data collected is applicable for comparing and summarising trends of the regular phenomenon, which can be used to generate theory or formula. However, they are not effective for drawing the patterning of characteristics of the lives of individuals, groups or institutions.

5.2.3.2. Qualitative methodology

Qualitative research is usually described as a large umbrella covering a broad range of techniques and philosophies (Hennink, Hutter & Bailey 2010). It is normally used to examine people's experiences in detail or to generate a theoretical understanding of social phenomena (Hennink, Hutter & Bailey 2010; Kanazawa 2017). The most distinctive feature of qualitative research is that it enables researchers to identify phenomena using the understanding, experience and knowledge gained from their study (Hennink, Hutter & Bailey 2010). Common research methods of this methodology are interviews, observation, life histories, focus group discussions, visual methods and content analysis. Table 5.3 illustrates the characteristics of qualitative research methods. According to Table 5.3, qualitative methodology is used to identify the ontological position that researchers established for interpreting their study and the way they understand the social world. Thus, the quality of research heavily depends on researchers' professionalism (Mason 2018).

Table 5.3. Characteristics of qualitative research and researchers

Qualitative research	**Qualitative researchers**
• takes place in the natural world • uses multiple methods • focuses on context • is emergent rather than tightly prefigured • is fundamentally interpretive	• view the social world holistically • systematically reflect on who they are • are sensitive to personal biography • use complex reasoning • conduct systematic inquiry

Source: Rossman & Rallis 2011

There are five common interpretive methods of qualitative methodology: case study, ethnography, grounded theory, phenomenology, and narrative enquiry. The content, advantages and limitations of each are summarised in Table 5.4.

Table 5.4. Summary of advantages and limitations of qualitative methods

Type of method	Description	Advantages	Limitations
Case study	A case study typically consists of a description of an entity and its action and offers explanations of why the entity acts as it does.	It permits a researcher to reveal the way a multiplicity of factors has interacted to produce the unique character of the entity that is the subject of the research.	The generalisations or principles drawn from one case or multiple cases can be applied to other cases only at considerable risk of error.
Ethnography	Ethnography is a special kind of case study in which the researcher participates in the activities of the people, organisation, or event being investigated over a period of time. It is the chief method used by cultural anthropologists.	It can serve several purposes, including revealing characteristics shared among members of a group – characteristics that render the group's culture distinctive, also exposing the internal operations of a group or organisation.	Researchers cannot expect ethnography to portray the "objective truth" about a group or organisation. Conclusions drawn from the ethnographic study of one group can be applied to other groups only at considerable risk because of the unique conditions that may determine the pattern of life in each setting.
Grounded theory	Grounded theory is a research method that employs a systematic set of procedures to develop an "inductively derived" grounded theory about a particular phenomenon.	It provides systematic procedures for shaping and handling rich qualitative materials, and the rigorous procedures enable researchers to check, refine and develop their ideas and intuitions about the data.	Researchers have to understand it is difficult for researchers, especially novices, to build the trustworthiness of their ability to identify when data collection should cease. Otherwise, misuse or abuse might occur.
Phenomenological research	Phenomenology seeks to understand and make explicit the subjective interpretation of the essence of human experience.	It is a very appropriate methodology to facilitate a meaningful understanding of the lived experience. In other words, it is the most appropriate method to study human activity.	It is challenging to determine sample size. A small sample size may lead to less reliability, but a large sample size may cause a common misunderstanding that the results should be statistically reliable. Gathering data and data analysis may be time-consuming and laborious.
Narrative research	Narrative research is stories about influential incidents in a person's own life.	It has the potential to demonstrate both the uniqueness of individuals' lives and the similarity among lives that are lived under different circumstances.	Narrative research is not an effective device for revealing how characteristics are distributed throughout a population.

Source: Charmaz & Belgrave 2007; Lai & To 2015; Lester 1999; Mason 2017; Sander 1982; Thomas 2003

A qualitative methodology can flexibly gather various types of information to analyse some issues without concern for quantities, but the research process cannot be easily copied from one case to another. In addition, the research results may become vulnerable due to the dependence on the quality of researchers.

This research aims to develop a model for deciding retrofitting strategies for office buildings. The model needs to be applied based on the evaluation of potential retrofitting activities' performance. Therefore, what process and criteria of assessment will be applied need to be clarified. It is also necessary to decide the theory foundation as the base to establish the decision model and how to verify the developed model to make sure it can work in practice. To cover the variety of data and study the issue in both broad and deep dimensions, the "within" mixed method is adopted in this study to determine assessment criteria and verify the developed model. Three data collection methods are chosen in this study: questionnaire survey, focus group discussion, and case study. The following sections explain why and how these methods are employed.

5.2.4. Data collection methods

The data needed for studying social phenomena is categorised into two types: primary and secondary data (Walliman 2016). Primary data is collected through observing, recording and measuring the activities and opinions of real people, inspecting objects, or experiencing events if the research target is an object or phenomena (Creswell & Creswell 2018; Walliman 2016). Secondary data is that gathered from purely literary works, such as newspapers and journals, and from drawings and photographs, fiction, databases, etc. It is used to understand the background of the study. For most research, this includes the resources explored for the literature review.

According to the traits of collected data, quantitative method and qualitative method are two main types of data collection methods. However, there is a trend to combine these two methods for broader and more reliable data collection, referred to as mixed method or multi-method according to different forms of combination.

5.2.4.1. Quantitative methods and qualitative methods

Quantitative methods and qualitative methods are two main types of data collection processes. Their benefits and limitations are summarised in Table 5.5 and Table 5.6.

Table 5.5. Summary of advantages and limitations of quantitative data collection methods

Data collection type	Content	Advantages	limitations
Questionnaire	The word questionnaire is typically used in a very general sense to mean any form (printed or digital) of questions that participants in a survey are asked to answer.	• They enable a researcher to collect a large quantity of data in a relatively short period of time. • The researcher does not need to be present at the time the information is provided, and data can be collected from people in distant places if the questionnaires are sent by regular mail or over the internet.	• Low reliability and validity of the research due to possible low return rate if the researcher is not present to supervise the participants as they complete the questionnaire. • Questionnaires rarely allow participants to receive clarification of confusing items, nor do questionnaires offer a convenient way for respondents to elaborate their answers and explain conditions that affect their opinions.
Inventories	Inventory means a document on which participants in a research project are asked to report their attitudes or preferences.	The strengths and weaknesses of inventories are the same as those of questionnaires.	
Measurement	Measurement links the theoretical framework of a survey-based study to its data-gathering instrument. Four different levels of measurement are usually distinguished: nominal, ordinal, interval, and ratio.	A higher level of measurement is not necessarily better than a low level of measurement. Standpoints refer to differences of perspective that give interesting angles on the same events or situation. Therefore, the benefits and limitations of measurement cannot be asserted without discussing the context.	

Source: Bhattacherjee 2012; Creswell & Creswell 2018; Olsen 2012; Thomas 2003

Table 5.6. Summary of advantages and limitations of qualitative data collection methods

Collection type	Options within type	Advantages	Limitations
Observations	• Complete participant: researcher conceals role • Observer as participants: role of the researcher is known • Participant as an observer: observation role secondary to participant role • Complete observer: researcher observes without participating	• Researcher has firsthand experience with participants • Researcher can record information as it is revealed • Unusual aspects can be noticed during observation • Useful in exploring topics that may be uncomfortable for participants to discuss	• Researcher may be seen as intrusive • Researcher cannot report “private” information that may be observed • Researcher may not have good attending and observing skills • Researcher may find it difficult to gain rapport with certain participants (e.g., children)
Interviews (structured, semi-structured & unstructured interviews)	• Face-to-face: one on one, in-person interview • Telephone: researcher interviews by phone • Video: researcher interviews by video such as Zoom • Group: researcher interviews participants in a group	• Useful when participants cannot be observed directly • Participants can provide historical information • Allows researcher “control” over the line of questioning • Interviewers can clarify any issues raised by the respondent or ask probing or follow-up questions.	• Provides indirect information filtered through the views of interviewees • Provides information in a designated place rather than the natural field • Researcher’s presence may bias responses • Not all people are equally articulate and perceptive • Time-consuming and resource-intensive
Focus group (more structured & less structured)	• Face-to-face: a small group of participants (typically 6–10) at one location • Video: a group of participants (6–10) have online meetings such as Zoom	• Useful to build a holistic understanding of the problem situation based on participants’ comments and experiences • Suited for exploratory research	• Internal validity cannot be established due to a lack of controls • The findings may not be generalised to other settings because of the small sample size
Documents	• Public documents such as minutes of meetings, and newspapers • Private documents such as journals, diaries, and letters • Email discussions	• Can obtain the language and words of participants • Can be accessed at a time convenient to the researcher – an unobtrusive source of information • Represents data that is thoughtful, as participants have given attention to compiling it • Saves researcher the time and expense of transcribing	• May be protected information unavailable to the public or private access. • Requires the researcher to search for the information in hard-to-find places • Materials may be incomplete • Documents may not be authentic or accurate
Audio-visual materials	• Photographs • Videotapes • Art objects • Computer software • Film	• May be unobtrusive method • Allows participants to directly share their “reality” • May be creative as it captures attention visually	• May be difficult to interpret • May not be accessible publicly or privately • Presence of an observer (e.g., photographer) may be disruptive and affect responses

Source: Bhattacherjee 2012; Creswell & Creswell 2018; Thomas 2003

5.2.4.2. Mixed method and multi-method strategies

Some researchers have strongly argued that qualitative and quantitative research should be regarded as complementary rather than opposites. The key differences between qualitative and quantitative research are listed in Table 5.7. Amaratunga et al. (2002) declared that the probability of failing to explore all components needed in a study is high if using only a single data collection method. Mason (2018) supported this point by stating that most researchers would apply a mixed method at some point to explore different aspects of the investigation. A combined qualitative and quantitative method for studying the same research problem was defined by Denzin (1978) as triangulation.

Table 5.7. Key differences between qualitative and quantitative research

	Qualitative research	**Quantitative research**
Objective	To gain a detailed understanding of underlying reasons, beliefs, motivations	To quantify data and extrapolate results to a broader population
Purpose	To understand why? How? What is the process? What are the influences or contexts?	To measure, count and quantify a problem. How much? How often? What proportion? Relationships in data.
Epistemological positions	Constructivist	Objectivist
Relationship between researcher and subject	Close/insider	Distant/outsider
Research focus	Meanings	Facts
The nature of data	Data based on textual materials	Data based on numerical materials
Study population	A small number of participants or interviewees are selected purposively (non-randomly) Referred to as participants or interviewees	A large sample size of representative cases Referred to as respondents or subjects
Data collection methods	In-depth interviews, observation, group discussions, etc.	Population surveys, questionnaires, exit interviews, etc.
Analysis	Analysis is interpretive	Analysis is statistical
Outcomes	To develop an initial understanding, to identify and explain behaviour, beliefs or actions	To identify prevalence, averages and patterns in data. To generalise to a broader population.

Source: Adapted from Gray 2014; Hennink, Hutter & Bailey 2010

With the development of both qualitative and quantitative research in social and human science, the application of data collection in both forms is expanding, and the desirability of mixed methods has been increasing in recent decades (Creswell 2003). Two types of triangulation (defined on page 128) are introduced: between-method and within-method (Singleton Jr & Straits 2018). “Between-method”, also called “cross-method”, is the most popular. Researchers use multiple methods to study the same dimension of one phenomenon; then, comparative data is yielded. The benefit is the certainty and reliability of the research results is increased if all results reach the same conclusion (Hennink 2014). The “within-method” uses multiple techniques to collect and interpret data. For example, the researcher can undertake a survey (quantitative method) to develop research using multiple scales or indices and then conduct interviews (qualitative method) to interpret the cause-and-effect behind the emergent theory.

Another term, “multi-method research”, is frequently mentioned with mixed methods. It investigates a social phenomenon using the combination of empirical research methods instead of single-shot studies to generate more reliable and accurate research results (Wood et al. 1999). Like mixed method, multi-method research is also at the level of method choice (Brewer & Hunter 2006). The coordination and comparison of different data collection methods (mainly the different observation ways) enrich the collective efforts to research findings. Eventually, it can make a firmer empirical base.

To conclude, quantitative and qualitative methods may be involved in the research process at different times and interact in different ways (Walliman 2016). Nevertheless, the mixed method emphasises the combination of quantitative and qualitative data collection methods in different forms: “between-method” triangulation assists the improvement of external validity while “within-method” triangulation allows cross-checking for internal reliability and conformance. Multi-method also allows the combination of either several qualitative or several quantitative methods.

This research adopts mixed method data collection methods. A questionnaire survey and focus group discussions are conducted in sequence to identify applicable retrofitting activities and generate suitable assessment criteria so that the conceptual model can be converted to an operating model. Then, a case study is conducted to quantify the operating model.

5.3. Research design

5.3.1. Research inquiry approaches

The strategies of inquiry are different types of inquiries within the selected quantitative, qualitative, mixed method or multi-method approaches that shape the direction and procedures of a research study (Creswell & Creswell 2018). In addition, the research design is deeply influenced by the research problem. After all, the purpose of undertaking research is to solve the research problem. All research elements should answer research questions, complete research objectives, and eventually solve the research problem (Creswell & Creswell 2018).

To plan research, the researcher needs to specify the need to employ quantitative or qualitative methodology, which implies the researcher's worldview and applied philosophical assumptions. Some typical paradigms are introduced to illustrate why and how to apply a particular research inquiry approach (Creswell & Creswell 2018):

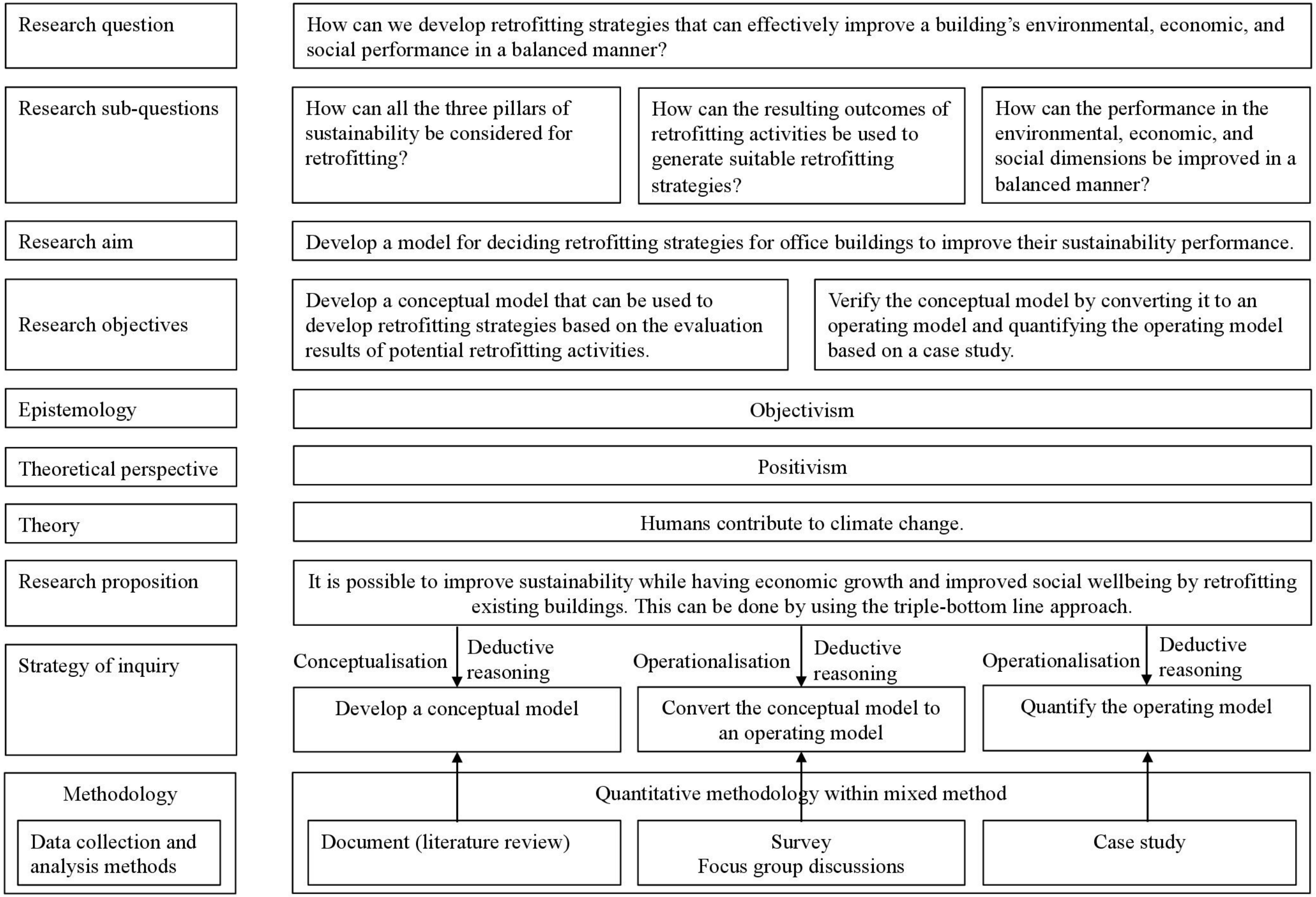
- The positivist worldview is adopted in quantitative research. Normally, the experimental design is applied, and the attitude of post-test measures is embedded in the research process.
- Qualitative research may hold the constructivist view to observe participants' behaviours, so an ethnographic design is needed. In addition, the stance of interpretive communities can also be found in qualitative research to interpret through individual interviews how participants have experienced oppression. A narrative design may be needed.
- For mixed method research, the pragmatic worldview is held, and both quantitative and qualitative data are sequentially collected for the best understanding and solving of the research problem.

In addition to the epistemology and theoretical perspective, suitable data collection strategies should be designed. In general, data collection strategies can be categorised into two types based on different reasoning approaches: positivist method and interpretive method (Bhattacherjee 2012). Positivist methods employ deductive reasoning to research, beginning with a theory about how things work and deriving testable hypotheses from it. Then, empirical data is collected to test the theoretical hypotheses (Bhattacherjee 2012; Walliman 2016). In contrast, interpretive methods employ inductive reasoning, beginning with data collection and attempting to generate a conclusion about the phenomenon of interest from the collected data

(Bhattacherjee 2012; Walliman 2016). In theory, positivist methods are used to test theory, while interpretive methods are used to build theory, but mostly there is some overlap between the two in practice to achieve a comprehensive data collection.

Considering what has been discussed above, the research design process for this study is illustrated in Figure 5.2. The research question, sub-questions, research aim and research objectives were identified in Chapter 1 and also consolidated in Figure 5.3. This study takes an objectivist stance of epistemology (referring to the discussion in Section 5.2.1). This study holds the theoretical perspective of positivism, even though both quantitative and qualitative data collection methods are employed (referring to the discussion in Section 5.2.2). A numerical calculation can provide the environmental and economic performance of retrofitting activities. As for social performance, a value score is used to express the performance level of retrofitting activities. Therefore, all of them are based on numerical data, and the process can be considered logical and reductionistic.

Figure 5.2. Process of research design



Research question	How can we develop retrofitting strategies that can effectively improve a building's environmental, economic, and social performance in a balanced manner?		
Research sub-questions	How can all the three pillars of sustainability be considered for retrofitting?	How can the resulting outcomes of retrofitting activities be used to generate suitable retrofitting strategies?	How can the performance in the environmental, economic, and social dimensions be improved in a balanced manner?
Research aim	Develop a model for deciding retrofitting strategies for office buildings to improve their sustainability performance.		
Research objectives	Develop a conceptual model that can be used to develop retrofitting strategies based on the evaluation results of potential retrofitting activities.	Verify the conceptual model by converting it to an operating model and quantifying the operating model based on a case study.	
Epistemology	Objectivism		
Theoretical perspective	Positivism		
Theory	Humans contribute to climate change.		
Research proposition	It is possible to improve sustainability while having economic growth and improved social wellbeing by retrofitting existing buildings. This can be done by using the triple-bottom line approach.		
	Conceptualisation Deductive reasoning	Operationalisation Deductive reasoning	Operationalisation Deductive reasoning
Strategy of inquiry	Develop a conceptual model	Convert the conceptual model to an operating model	Quantify the operating model
Methodology	Quantitative methodology within mixed method		
Data collection and analysis methods	Document (literature review)	Survey Focus group discussions	Case study

Chapter 3 discussed that existing office buildings are responsible for massive negative impacts on the natural environment. In addition, regarding the theory that humans contribute to climate change, the research proposition is that it is possible to improve sustainability while potentially allowing economic growth and improved social wellbeing by retrofitting existing buildings using the triple-bottom line approach. In research, the theoretical proposition consists of relationships between abstract constructs, and careful measurement of these constructs is necessary to test the theoretical proposition (Bhattacherjee 2012).

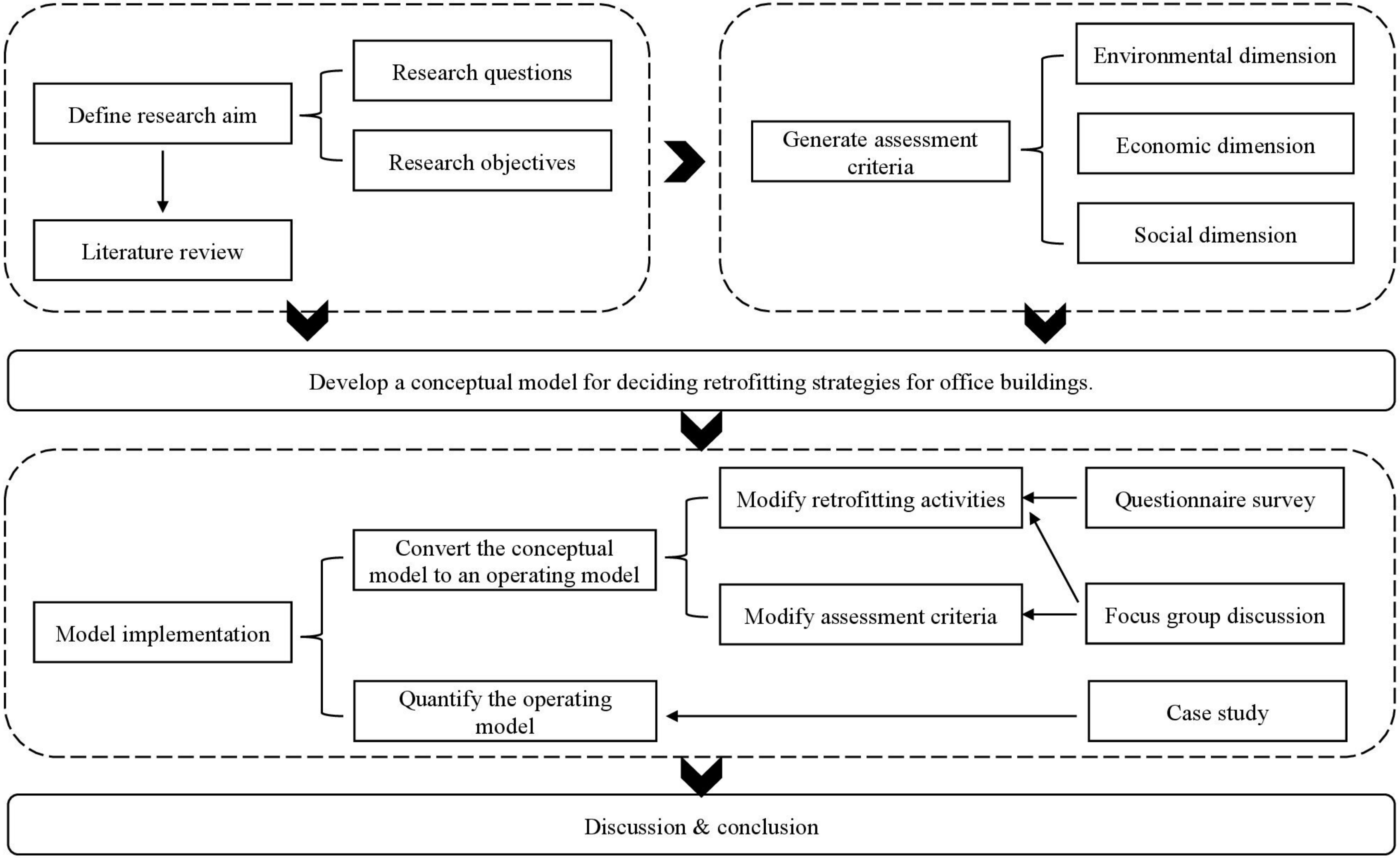
In general, constructs in research can be measured by the processes of conceptualisation and operationalisation (Bhattacherjee 2012). Conceptualisation refers to the mental process by which vague and abstract constructs (concepts) and their constituent parts are defined in concrete and precise terms. Once a theoretical construct, or conceptual model, is defined, the process of operationalisation should be conducted to measure it. Therefore, operationalisation refers to the process of quantification that develops indicators or items to measure the constructs (Bhattacherjee 2012).

This study adopts a positivist data collection strategy (deductive reasoning approach) to test the research proposition. First, a conceptual model for deciding retrofitting strategies using the triple-bottom line approach is developed based on literature review (conceptualisation). Then, the conceptual model is converted to an operational model by specifying retrofitting activities and assessment criteria (operationalisation). The operating model is then quantified via a case study (operationalisation). As a result, the conceptual model considers all the various strategies for retrofitting, and the operating model is a quantified set for a specific location or region. The whole process can test whether the research proposition is correct or not. Then the process from converting the conceptual model to an operating model to quantifying the operating model using a case study can be recognised as a logically and methodologically correct framework for the work done and to be done in the future. By copying the process, the conceptual model can be adapted according to the specific situation of each retrofitting project and used to develop retrofitting strategies.

5.3.2. Research process

Based on the discussed research design, the research process is illustrated in Figure 5.3. The research aim, objectives and questions were identified in Chapter 1. Existing literature relevant to sustainable retrofitting and assessment methods of sustainability was reviewed to understand the development of sustainable retrofitting and identify general assessment criteria in environmental, economic and social dimensions (see Chapters 2 to 4). A conceptual model for deciding retrofitting strategies for office buildings is also developed based on the literature review (see Chapter 6). To verify and demonstrate the conceptual model, it needs to be converted to an operating model first (see Chapter 7). Then, the operating model is applied to the case building to develop the retrofitting strategies that can improve sustainability in environmental, economic and social dimensions (see Chapter 8).

Figure 5.3. Research flowchart



5.3.2.1. Converting the conceptual model to an operating model

A conceptual model is designed to be generic, which means it can be adapted in any country, region or place. Therefore, it has to be modified for local situations before use. To illustrate that the conceptual model can be converted to be operational in reality, China is selected as the place where the model is verified and demonstrated. China is the most populous developing country in the world and has a large number of buildings built in the past 30 years, now due for retrofit. In addition, China has regions with varying climate conditions, making it a good opportunity to test the flexibility of the conceptual model.

An operating model is defined as a bridge between strategies and operational activities (Bateman 2017). It works as a blueprint for a building that can capture the design team's critical decisions that others can conveniently refer to during the transformation (Campbell & Gutierrez 2021). However, the operating model is more dynamic than a blueprint for regular changes (de Vries et al. 2011). The complexity and uncertainty make it challenging to interpret an operating model (de Vries et al. 2011).

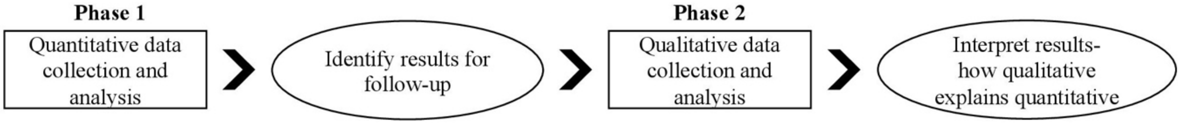
Different frameworks are used to define elements that compose an operating model. The framework developed by de Vries et al. (2011) uses people, process and technology to structure an operating model. A new operating model from McKinsey has three elements: structure, processes and people (Álvarez et al. 2022). Campbell and Gutierrez (2021) developed an operating model covering six elements: process, organisation, location, information, suppliers and management. Meanwhile, Campbell and Gutierrez (2021) concluded three steps for transforming strategies into implementation, which are the essence of operating models:

- Step 1. Design changes to current organisation
- Step 2. Transform organisation guided by the design
- Step 3. Lead the transformed organisation

In this study, the operating model is not created from scratch but converted from the conceptual model. Most elements, such as process, people and general information, have been defined in the conceptual model. Therefore, the conversion process is mainly for designing changes to suit the local situation such as the local market, specific structure, activities, climate, and culture. The changes in the model are retrofitting activities and assessment criteria, which should be modified according to the specific local situation mentioned above. Therefore, these two elements are determined during the conversion process.

To identify suitable retrofitting activities and assessment criteria for the case building, opinions from key stakeholders need to be collected, such as building owners and tenants, and professionals in the construction and property sector, such as engineers, architects, project managers and facility managers. As discussed in Section 5.2.4, different data collection methods are available to gather people's opinions, and suitable one(s) can be selected according to the specific situation of the conducted retrofitting project. In this study, an office building in Hangzhou, China is used to conduct the case study (See Section 7.2 in Chapter 7). Considering the large size of territory and different climate zones in China, the within mixed method is adopted to collect data from the broad to the specific. An explanatory sequential design or two-phase design, as Figure 5.4 shows, is conducted (Creswell & Creswell 2018).

Figure 5.4. Explanatory sequential design



Source: Creswell & Creswell 2018

The quantitative method is used in the first phase. In this study, a questionnaire survey is conducted in northern and southern China to broadly identify applicable retrofitting activities and assessment criteria for retrofitting projects in China (See Section 7.4.1 in Chapter 7). The quantitative results from the first phase typically inform the types of participants in the second phase (Creswell & Creswell 2018). The data from the second phase helps provide more depth and insight into the quantitative results (Creswell & Creswell 2018). Therefore, in this study, the same type of respondents to the survey are also invited as participants in the second phase – the focus group discussions (See Section 7.4.2 in Chapter 7). Focus group discussions can explain outcomes of the questionnaire survey. Moreover, consensus on suitable retrofitting activities and assessment criteria for the case building can also be reached via group discussions. In this way, the conceptual model can be converted into an operating model, which is ready to be applied in the case study.

5.3.2.2. Quantifying the operating model

The last step in demonstrating validity of the conceptual model is to conduct a case study (See Chapter 8). Orum, Feagin and Sjoberg (1991, p. 2) defined a case study as "an in-depth, multifaceted investigation, using qualitative research methods, of a single social phenomenon". Case study method enables the researcher to take a complicated and broad topic, or phenomenon, and condense it into a manageable research question (s). By collecting data from qualitative and/or quantitative datasets, a deeper understanding of the topic or phenomenon can be acquired than using only one type of data (Heale & Twycross 2018). Case study method can be used to both test propositions (positivist method) and build a theory (interpretive method) (Bhattacherjee 2012). In this study, a case study is conducted to test the research proposition. The expected result of the case study is that a preferable retrofitting strategy (within project constraints) can be developed for the case building by considering the three sustainability pillars.

5.3.2.3. Language and ethics

Since the case study is conducted in China, the survey and focus group discussions were conducted in Chinese to communicate with respondents and participants effectively and accurately. The questionnaire form was created in English first, then translated into Chinese. Both English and Chinese versions were sent to professionals who can speak both languages to check whether the translation is accurate. The Chinese questionnaire form was only distributed after the professionals confirmed that the translation did not distort the meaning. For the focus group discussions, recordings were transcribed and analysed in Chinese. Then the analysis results were translated into English to reduce the risk of invalid analysis results due to inaccurate translation. In addition, it can also reduce the workload of translation review as only the analysis results need to be translated.

Ethical issues have to be considered when conducting research. Gajjar (2013) introduced five reasons why ethical consideration is essential for academic research. First, the development of norms is essential for pursuing knowledge and truth, which is the aim of doing research. Second, many different people with different cultures, religions and backgrounds are involved in research. The value generated by ethical standards, such as trust and respect, can help build the bridge of cooperation and coordination. Third, ethical standards can ensure researchers abide by the policy of public responsibility. Fourth, public trust in research can also be built by ethical norms. Finally, many ethical considerations of research can also promote other social values, like health and safety, human rights, and social welfare. According to the Australian Code for the Responsible Conduct of Research (2007, p. 1.3), the below ethical concerns of research should be considered:

- honesty and integrity
- respect for human research participants, animals and the environment
- good stewardship of public resources used to conduct research
- appropriate acknowledgment of the role of others in research
- responsible communication of research results.

Ethical consideration is an indispensable part of this research because different people are involved when conducting the questionnaire survey, focus groups and case study. In this study, respondents of the survey and participants of focus group discussions are kept anonymous. In the analysis, their identity is represented as symbols without allegorical meanings, such as A and B. The collected questionnaire forms and recordings of focus group discussions are encrypted and stored in a computer to which only the researcher and the supervisors have access. Furthermore, all the participants were informed before participating in the research that their identity would not be revealed in any form, and they could quit at any time without giving a reason. All these ethical issues were considered in the application for ethical approval, which was submitted to the UTS Human Research Ethics Committee. The study received ethics approval (No. UTS HREC ETH18-2810), and data collection was conducted by following the requirements in the ethics approval.

5.4. Summary

This study aims to develop a model for deciding retrofitting strategies for office buildings to answer the research question: how can we develop retrofitting strategies that can effectively improve a building’s environmental, economic and social performance in a balanced manner? To achieve the research aim and answer the research question, the epistemological stance of objectivism is taken because the fact that the sustainability performance of existing buildings can be improved by using suitable retrofitting strategies will not be affected by who the researcher is or who is involved in the process. For the theoretical perspective, the stance of positivism is held because developing the model is an objective process. It addresses that retrofitting strategies can improve the sustainability performance of existing office buildings. It will not change with the different opinions of different people.

To justify the validity of the conceptual model, the research is designed as a process of giving a research proposition and testing the proposition via a measured process of conceptualisation and operationalisation. Based on the theory that humans contribute to climate change, the research proposition is that it is possible to improve sustainability while having potential for economic growth and increased social wellbeing by retrofitting existing buildings; and it can be done by using the triple-bottom line approach. Then, the proposition is conceptualised as a conceptual model that can be used to decide retrofitting strategies for office buildings. The next step is to convert the conceptual model to an operating model (operationalisation) by specifying retrofitting activities and assessment criteria to suit the local situation of the case building. A case study is conducted to quantify the operating model. As a result, the validity of the conceptual model can be justified, which reflects that the research proposition is correct.

With a clear understanding of how this research is designed, the next chapter describes the process of developing the conceptual model. The data from the questionnaire survey and focus group discussions is analysed in Chapter 7, which illustrates the process of converting the conceptual model to the operating model for the case building. Chapter 8 conducts a case study demonstrating how an optimal retrofitting strategy can be developed using the operating model.

Chapter 6. Development of a conceptual model for developing retrofitting strategies for office buildings

6.1. Introduction

Chapters 2 to 4 reviewed existing studies about sustainable development, sustainable retrofitting, and assessment methods of sustainable construction. Based on the literature review, it can be stated that existing buildings are responsible for massive negative impacts on the natural environment, and building retrofitting is regarded as an effective remedy for the poor performance of existing buildings. It is also the last chance for existing buildings to achieve sustainability. Regarding this situation and requirements of sustainable construction, a research proposition is proposed: it is possible to improve sustainability while having economic growth and social wellbeing by retrofitting existing buildings using the triple-bottom line approach.

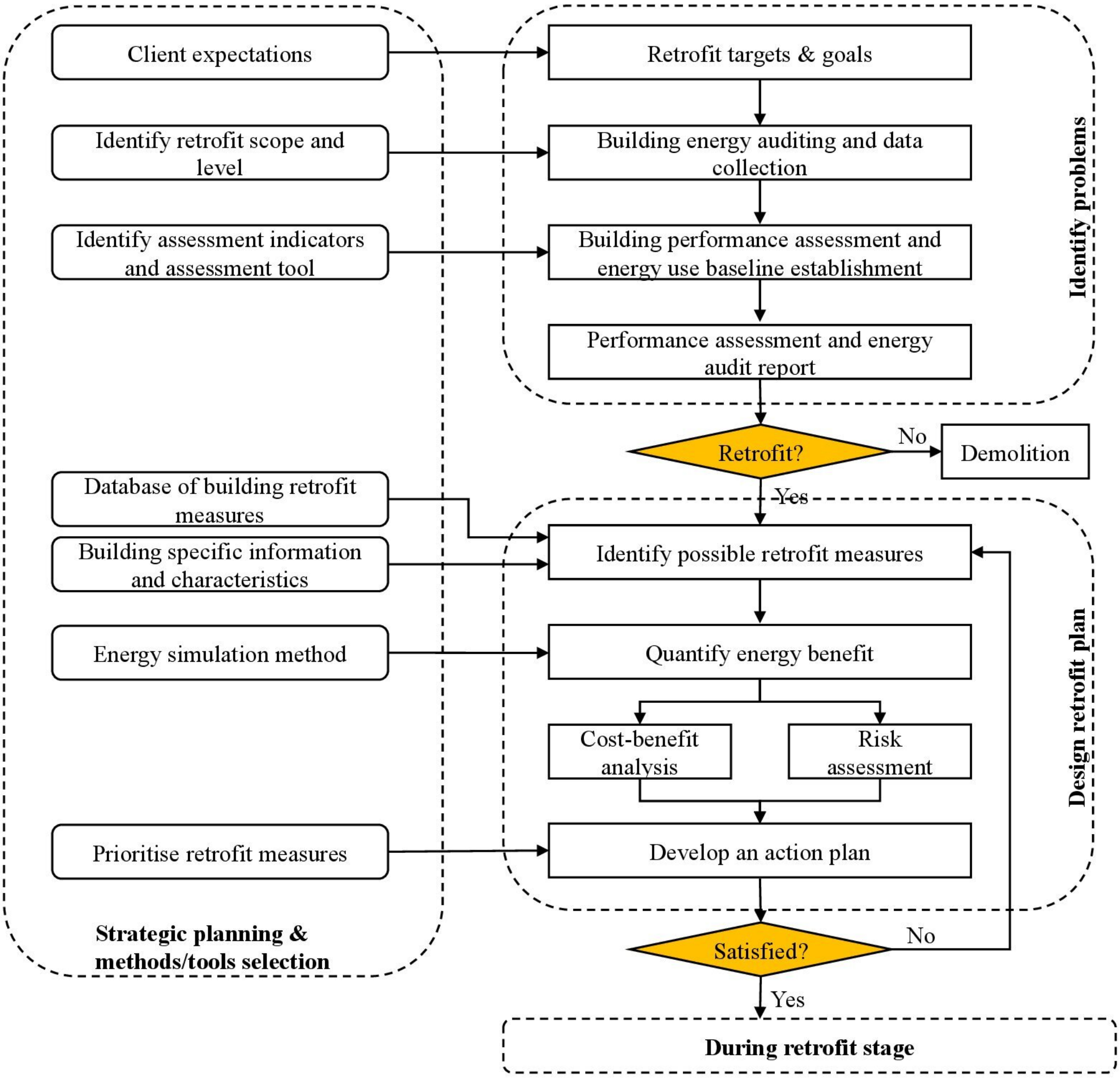
To test this research proposition, a conceptual model is developed in this chapter, which can consider all three sustainability dimensions when applying it to develop retrofitting strategies for office buildings. First, the general steps of MODM and the requirement of retrofitting projects are reviewed and adapted to develop the conceptual model. Then, details about each step of the conceptual model are elaborated.

6.2. Model development

Based on the research proposition, the conceptual model should be able to develop a retrofitting strategy that addresses and balances environmental, economic and social concerns complying with the principles of the triple-bottom line approach. However, the three pillars of sustainability often compete with one another. For example, the improved performance of an existing building by a retrofitting activity, such as improving indoor comfort performance by installing a powerful HVAC system, usually means high initial cost and/or unfavourable social impacts from the installation. Apart from the three sustainability pillars, the developed retrofitting strategy should also be able to satisfy project constraints. Regarding multiple conflicting issues that need to be dealt with, as discussed in Section 4.5.3 of Chapter 4, MODM is a suitable decision-making methodology for this study. MODM enables dealing with conflicting, even non-commensurable issues by creating a vector based on the assessment criteria relating to the decision, objective functions, and problem constraints (Asmone & Chew 2018).

As discussed in Chapter 3, retrofitting is more complex than new construction. A study by Ma et al. (2012) revealed the general process of building retrofitting by considering the ability to reduce energy consumption and improve cost efficiency of existing buildings by retrofitting. The whole retrofit process is divided into three stages: pre-retrofit stage, during retrofit stage, and post-retrofit stage. The pre-retrofit stage is mainly about selecting and amalgamating activities as retrofitting plans shown in Figure 6.1. The during retrofit stage is about implementing and commissioning the retrofitting strategy. The post-retrofit stage is for measuring and verifying results of the determined retrofitting strategy.

Figure 6.1. Retrofit process at pre-retrofit stage



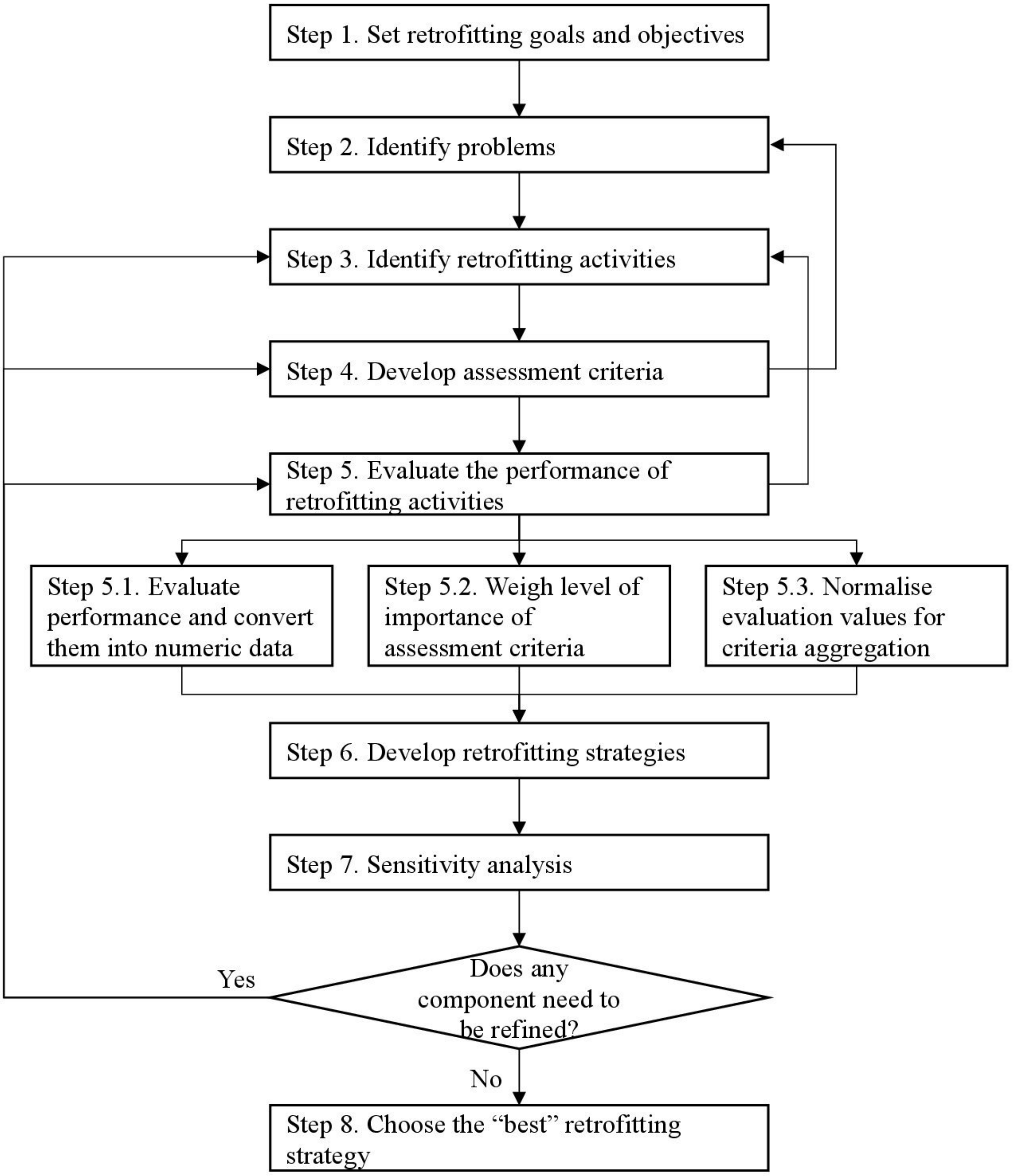
Source: Adapted from Ma et al. 2012

Based on Figure 6.1, the process at the pre-retrofit stage mainly consists of two parts: identifying problems of the existing building to decide whether retrofitting or demolishing is a feasible solution, and designing a retrofitting plan if it is decided the building is to be retrofitted. Therefore, the part labelled identifying problems in Figure 6.1 is simplified into two steps in the conceptual model: set retrofitting goals and objectives, and identify problems of the retrofitted building.

The developed retrofitting plan in Figure 6.1 is to reduce the energy consumption of the existing building with consideration of cost efficiency. Therefore, energy efficiency is the main objective. However, the conceptual model developed in this study considers all the environmental, economic and social dimensions of sustainable development. Different retrofitting activities may be proposed to meet different retrofitting objectives, such as improving energy efficiency, improving water use efficiency, improving indoor environmental quality, decreasing operation cost, and/or improving accessibility to building facilities and services. As the general MODM model indicated in Figure 4.6 (a) in Chapter 4, the performance of an individual retrofitting activity is assessed based on identified assessment criteria. However, whether an activity can be selected for developing a retrofitting strategy is not purely determined by the evaluation results but also how well the amalgamation of different retrofitting activities can satisfy project constraints. Therefore, compared to the general MODM model shown in Figure 4.6 (a), one particular step is added in the developed conceptual model – develop retrofitting strategies that can meet retrofitting objectives and satisfy all project constraints at the same time.

By considering elements in MODM and the required steps for generating retrofitting strategies, a conceptual model for deciding retrofitting strategies for office buildings is developed, as Figure 6.2 shows. The conceptual model represents a relatively linear process of decision making but with several feedback loops. In fact, the methodology of MODM is an iterative process that allows decision makers to add new information and refine decisions (Brownley 2013; Geneletti 2019). Each step contained in the conceptual model is discussed in great detail in the following sections.

Figure 6.2. The conceptual model of deciding retrofitting strategies for office buildings



6.3. Set retrofitting goals and objectives

The first step of the process is to set retrofitting goals and objectives. Retrofitting goals are thresholds regarding different criteria for measuring whether alternatives achieve or not, while objectives indicate the desired direction of achievement (Ekel, Pedrycz & Pereira Jr 2020). For example, if a retrofitting objective is set to improve energy efficiency, the associated retrofitting goal can be to achieve a 30% energy saving. Setting retrofitting goals and objectives requires the retrofitting team to gather different perspectives and opinions on the decision situation, such as the requirements and needs of clients (building owners or investors) via consultation, and the demands of users, such as tenants and service staff, via interviews or surveys.

In addition, project constraints such as the financial, political and external also need to be identified at the early stage of the decision-making process (Nijkamp, Rietveld & Voogd 1990). Financial constraints are related to factors that restrict the amount or quality of project development, such as the budget of projects. Political constraints refer to regulations and policies that affect the direction of development. External constraints should also be considered, which are influenced by the development impacts on the community and the natural environment, reflecting the environmental and social requirements of sustainability. Investigation of project constraints at the early stage of a project is crucial to identify precise alternatives contributing to minimising the gap between the generated solution and the desired outcome (Nijkamp, Rietveld & Voogd 1990).

With the above information in mind, a retrofitting team can identify objectives and structure an initial, general frame of evaluation, including priority ranking of objectives, assessment criteria, and associated assessment methods to quantify performance of retrofitting activities. Identifying objectives is one of the most challenging decision-making processes since it needs constructive thinking and creation based on raw information. Success in this step significantly contributes to optimising alternative solutions (Brownley 2013).

6.4. Identify problems of the proposed building

The second step involves identifying the problems of the proposed building. Usually, a walk-through is undertaken first for a preliminary and rough check of where the problems are. Then, a building audit is conducted to diagnose the problems of the building and provide decision makers with a whole picture of the situation of the proposed building. The retrofitting scope can also be defined based on the audit result.

There is no doubt that a problem can have impacts on different sustainability dimensions. For example, a lack of building management control system may lead to high energy consumption and high operation cost (environment and economic dimensions), and tenants do not have a building where the indoor temperature, humidity, and dimming light level cannot automatically adjust with the change of outside climate (social dimension) Another example is that the existing HVAC system is outdated, and its components are not easily available. Therefore, it may be difficult and expensive to get replacements if the components break, leading to high maintenance cost and poor maintainability. Based on the literature review, Table 6.1 summarises the primary problems of existing office buildings on environmental, economic and social dimensions.

Table 6.1. Common problems with existing office buildings

Environmental problems	Economic problems	Social problems
• High energy consumption • Massive greenhouse gas emissions • Use of materials with a short life span • High water consumption • Excessive waste generation • Poor indoor environmental quality	• High operation cost • High maintenance cost • High vacancy rate due to poor performance	• Some building services are not provided, such as a lack of building management control system which can automatically adjust indoor temperature, humidity, dimming level with changes of outside climate • Lack of building facilities for people with additional needs, including disabled people, pregnant women, the elderly, etc. • Safety and security issues • Difficulty in cleaning and maintaining the building

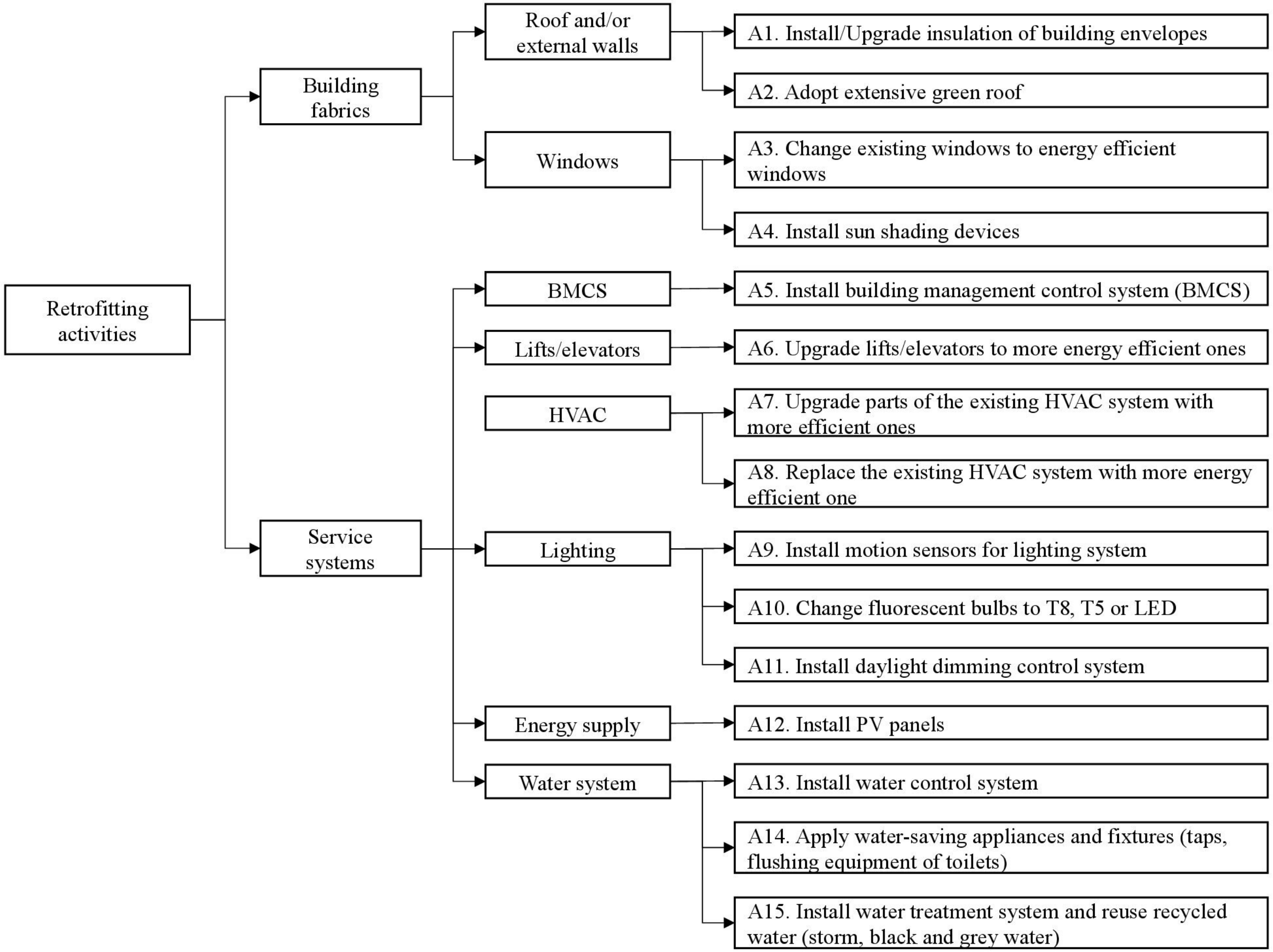
Source: Ascione et al. 2017; Cellura et al. 2013; Dolezal & Spitzbart-Glasl 2015; Dwaikat & Ali 2016; Kylili et al. 2016; Liang et al. 2018; Oregi et al. 2017; Wong & Zhou 2015; Wu et al. 2014

By understanding the problems the existing building has, building owners or investors may get a better understanding of why the building performs as it does. Meanwhile, based on audit results, they may modify retrofitting goals and objectives set in the first step by adding objectives or emphasising the expectation of improvement on a specific aspect. Then the decision-making process will restart from the beginning like the loop shown between the first two steps in Figure 6.2.

6.5. Propose retrofitting activities

Regarding each identified problem from the last step, relevant retrofitting activities that may solve those problems can be proposed based on the expertise of the retrofitting team in the problem area. In addition, identifying retrofitting activities also significantly depends on the cost and availability of information (Ekel, Pedrycz & Pereira Jr 2020). Table 3.1 in Chapter 3 lists 15 common retrofitting activities for office buildings based on the literature review. Based on building components where retrofitting activities are implemented, these common retrofitting activities can be categorised into two groups, as Figure 6.3 shows. Figure 6.3 can be used as a checklist for selecting suitable retrofitting activities for proposed projects. When using this conceptual model on a real case, the retrofitting team can substitute, expand, delete or modify these retrofitting activities to suit the specific situation of the case.

Figure 6.3. Common retrofitting activities for office buildings



How and when to stop identifying retrofitting activities is a crucial issue. Based on the study by Ekel, Pedrycz and Pereira Jr (2020), the number of retrofitting activities is defined in terms of identified objectives and decision problems. In this conceptual model, to make sure the developed retrofitting strategy is the optimal solution regarding existing project constraints, all the potential activities should be identified first. If the set of suitable alternatives for solving one problem is too large, a screening process may be adopted to reduce the number, making them viable and manageable. The screening process prioritises proposed activities based on key elements of the project, such as cost, availability of local materials, construction technologies, etc. In other words, the screening process identifies the scope of impact assessment, which controls the cost and time of the assessment (Dougherty & Hall 1995).

6.6. Develop assessment criteria

This step is related to developing assessment criteria for evaluating the performance of proposed retrofitting activities. Criteria are desired attributes of solutions to decision problems, and alternatives are measured against criteria to see how well they solve the decision problems (Jones & Tamiz 2010). Correspondingly, assessment criteria for green buildings reflect aspects of benefits that a green building should have or produce.

Assessment criteria can be identified via four different processes according to different traits of projects. The first method is to identify assessment criteria based on retrofitting goals and objectives when they are the only concerns of the project. The second one is to identify assessment criteria through the retrofitting team that has a deep understanding of the situation of the project. Then, they identify assessment criteria based on their expertise and with the consideration of the needs of clients, requirements of different stakeholders, and project constraints. The third method is to identify assessment criteria purely based on a literature review. Table 6.2 summarises environmental, economic and social assessment criteria that are suitable for assessing the performance of existing buildings based on the literature review. Similar to Figure 6.3, Table 6.2 can also be modified according to the specific situation of the retrofitting project, which makes the conceptual model operational. The last method is to have public participants joining in the process so that the external influence of the project can also be identified, such as the impact of construction on people randomly visiting the building, passing by the building, and living or working in the neighbouring buildings.

Table 6.2. Assessment criteria of retrofitting

	Life stage	**Assessment criteria**		**References**
Environmental	Retrofitting stage	E1. Energy efficiency	E1-1. Embodied energy of materials	Luzkendorf & Lorenz 2005; ISO 2006; Kylili, Fokaides & Jimenez 2016; Mahmoud, Zayed & Fahmy 2019
			E1-2. Energy consumption by retrofitting activities	
		E2. Carbon emissions	E2-1. Embodied carbon emissions of materials	
			E2-2. Carbon emissions of retrofitting activities	
		E3. Material use	E3-1. Use reusable/recyclable materials and components	
		E4. Waste generation	E4-1. Waste generation from retrofitting activities	
	Operation stage	E1. Energy efficiency	E1-3. Embodied energy from materials for maintenance, repair, and replacement	
			E1-4. Energy consumption of operation activities	
		E2. Carbon emissions	E2-3. Embodied carbon emissions from materials for maintenance, repair, and replacement	
			E2-4. Carbon emissions of operation activities	
		E3. Material use	E3-2. Use reusable/recyclable materials and components	
		E4. Waste generation	E4-2. Waste generation from maintenance, repair, and replacement	
		E5. Indoor environmental quality	E5-1. Indoor thermal comfort	
			E5-2. Indoor visual comfort	
			E5-3. Indoor acoustic comfort	
		E6. Water efficiency	E6-1. Water consumption of operation activities	
Economic	Retrofitting stage	EC1. Initial (retrofitting) cost		Wang, Xia & Zhang 2014; Kylili, Fokaides & Jimenez 2016; ISO 2017
	Operation stage	EC2. Operation cost		
		EC3. Maintenance cost		
		EC4. Repair cost		
		EC5. Replacement cost		
Social	Retrofitting stage	S1. Impact on neighbourhood	S1-1. Noise impact on the neighbourhood	BSI 2014; Kylili, Fokaides & Jimenez 2016; Orlowski & Radziejowska 2017; Santos et al. 2017; Zarghami & Fatourehchi 2020
			S1-2. Emission impact on the neighbourhood (e.g., particulate matters, dust from retrofitting construction)	
		S2. Safety	S2-1. Site safety during retrofitting	
		S3. Impact on cultural heritage	S3-1. Damage to cultural heritage	
	Operation stage	S4. Accessibility	S4-1. Accessibility to building facilities for people with special needs	
			S4-2. Accessibility to building services (such as automatically adjusted indoor temperature, humidity, and dimming level by BMCS)	
		S5. Maintenance and maintainability	S5-1. Impact on maintenance and maintainability from newly added building fabrics or building systems	

The process of developing assessment criteria can also remind the retrofitting team that there may be other problems they neglected in Step 2 (Section 6.4). If any, they should be added, and the decision-making process should restart from Step 2 (Section 6.4).

6.7. Evaluate performance of retrofitting activities

The fifth step is to evaluate the performance of retrofitting activities. It is achieved by analysing the performance of proposed retrofitting activities by measuring their ability to satisfy each assessment criterion. To aggregate evaluation results as one, normalisation is employed to convert evaluation into unitless values. In this step, the level of importance of assessment criteria is considered by integrating a weighting system. In this way, a weighted assessment score can be attained for each retrofitting activity, which can be used to develop retrofitting strategies in the next step (Section 6.8). These three sub-steps are explained as follows.

6.7.1. Evaluate performance and convert to numerical data

Both quantitative and qualitative issues are included in the identified assessment criteria from the last step. The techniques for measuring quantitative criteria are well-developed and have been applied for decades. The difficulty in this step is quantifying subjective assessment criteria. The evaluation methods for assessing objective and subjective criteria are discussed below.

6.7.1.1. Evaluation of objective criteria

Most of the criteria under the environmental and economic dimensions are objective criteria. As discussed in Chapter 4, LCA is one of the most widely used methods to quantify the environmental impacts of construction projects. It is adopted in this model to evaluate the environmental assessment criteria from Table 6.2, including embodied energy, carbon emissions, water efficiency, use of reusable/recyclable materials, and waste generation. If data or information is not available to undertake an LCA study, simulation tools can be adopted to simulate the environmental performance of retrofitting activities, such as indoor environmental quality.

When retrofitting using the LCA methodology, the system boundary, study period and functional unit need to be defined first based on EN 15978 (CEN 2011). Figure 4.1 in Chapter 4 illustrated the modular information for different stages of the building assessment contained in LCA. Since this step is to assess the difference by retrofitting activities, which mainly occurs in the retrofitting stage and operation stage, the cradle-to-use system boundary is taken, including modules A1 to A5 at the product and construction process stages, and modules B2 to B7 at the use stage.

Based on EN 15978 (CEN 2011), the energy and water consumption in the operation stage is calculated. However, in this study, comparing the amount of consumption, the saving on energy and water use is more desired, representing the ability of potential retrofitting activities to improve the building's energy efficiency and water efficiency. Accordingly, the calculations required in the conceptual model include:

Modules A1 to A3	Includes energy use by extracting, transporting and manufacturing raw materials into materials or products at product stage.
Modules A4 and A5	Includes energy use by transporting to site and installing the manufactured materials or products on site.
Modules B2 to B5	Includes the energy saving by retrofitting activities from maintaining, repairing and replacing the upgraded building systems and/or components during the operation stage.
Modules B6 and B7	Includes energy saving and water saving from operating the newly installed building components or systems during the operation stage.

The whole building is defined as the functional unit for this study since the improvement by implementing the developed retrofitting strategy is evaluated for the whole building. The residual service life of retrofitted buildings also influences evaluation results. As discussed in Chapter 4, if residual service life can be estimated, modules B2 to B7 can be assessed based on it. If it cannot be estimated, a service life of 50 years can be regarded as an acceptable study period (Desideri & Asdrubali 2018). With the system boundary and functional unit defined, environmental impacts can be evaluated using the assessment criteria previously developed.

(1) Energy use and carbon emissions

At the retrofitting stage, embodied energy (EE) and embodied carbon (EC) emissions of building materials, and energy consumption and carbon emissions at retrofitting construction are evaluated. Two methods are available to calculate them. First, LCA software, such as Gabi, Simapro, Umberto and openLCA, can be used to evaluate embodied energy and embodied carbon emissions of materials from retrofitting activities (Silva et al. 2019). However, most software packages include only one database and assessment model (Kalverkamp & Karbe 2019; Pauer, Wohner & Tacker 2020). Even when some software, like GaBi and SimaPro, has more than one database to choose from, it cannot guarantee that an updated database for every country is available. Therefore, local variations may be an issue in using simulation software.

Another method is using embodied energy and materials' carbon coefficients to calculate the consumption and emissions. It can be realised by multiplying them with the quantity of installed materials. The coefficients vary with advancement of technology and different locations. In the long term, technology may have impacts on determining the carbon emission coefficient, but in the short term, such impacts will be at the margin. Due to different fuel sources and methods of extracting raw materials, manufacturing and transportation, the coefficients are different in different locations. Therefore, the latest updated local data about embodied energy and embodied carbon emissions should be adopted when implementing the model in a real retrofitting case. However, it is often challenging to obtain local data of embodied energy and materials' carbon coefficients. The Inventory of Carbon and Energy (ICE) developed by the Department of Mechanics of University of Bath (UK) provides data about embodied energy and materials' carbon coefficients (Hammond & Jones 2011). It is often used as a data resource to calculate embodied energy and carbon of building materials, such as in the study by Rodrigues et al. (2018) and the study by Zeitz, Griffin and Dusicka (2019). However, as discussed above, relying on one data resource cannot deal with local variations. Therefore, the local data adopted from existing studies and literature may contribute to more accurate evaluation results. A database, such as ICE, can be used as a supplement if no local data is available. Indeed, there is a compromise between what is theoretically correct and what is reasonable accuracy in practice. The accuracy of evaluation will be affected by the available data. It is important to get as much data as possible that can reflect the local situation.

The energy consumed and carbon emitted on the construction site are evaluated based on the quantity, type, power and working duration of equipment and machines used on the retrofitting site. The data can be obtained by consulting with specialists who are familiar with retrofitting construction. Alternatively, the data from existing studies in which the same retrofitting activities are used to retrofit a building of similar scale can be adopted.

In the operation stage, recurrent embodied energy and carbon emissions from replacement and operation energy consumption and carbon emissions are taken into account. Recurrent embodied energy and embodied carbon emissions are the aggregation of embodied energy and embodied carbon emissions of the installed building components during the residual lifetime of the building. Energy consumption by operating building service systems can be estimated using simulation tools or calculating the usage based on the quantity, power and operation hours of electricity-related building systems. The amount of carbon emissions can be attained based on the conversion relation with the type of energy supplied for the building. For example, the national database in the US, the Emission and Generation Resource Integrated Database (eGRID), can be used as a data resource to estimate the environmental characteristics of most electric power generated in the US (EPA 2022). The study by Xu, Schwarz and Yang (2020) summarised the carbon emission coefficients for coal, oil, natural gas and hydro-electricity by four institutes, as Table 6.3 shows. Again, the coefficients vary with advancement of technology and different locations. The latest updated local data should be adopted.

Table 6.3. Carbon emission coefficients

Data resource	**Carbon emission coefficients**			
	Coal (tonne/tonne)	**Oil (tonne/tonne)**	**Natural gas (tonne/million cubic metre)**	**Hydro & nuclear**
Institute of Energy Economics, Japan	0.756	0.586	0.449	0
US DEO/US EIA	0.702	0.478	0.389	0
Chinese State Scientific & Technological Commission: Climate Change Program	0.726	0.583	0.409	0
Chinese Energy Research Institute	0.748	0.583	0.444	0

Source: Xu, Schwarz & Yang 2020

(2) Water use

The saved water use in the operation stage is calculated in this study. In contrast to estimating energy consumption, simulation tools are rare for estimating water use by buildings (Bertone et al. 2016). The common way to estimate water use by buildings is based on statistical data (Bertone et al. 2016). However, data collection is also a challenge to estimate water saving by retrofitting (Bertone et al. 2016; Bertone et al. 2018). The retrofitting team needs to conduct a statistical survey to collect data about how much water can be saved by implementing potential retrofitting activities. Alternatively, the necessary data, such as the flow rate of taps, use frequency and time of each use, can be collected through existing publicly available sources.

(3) Waste generation

In the retrofitting stage, waste is mainly from removing obsolescent building materials and components. However, the materials are removed due to their poor performance, which means they will be removed anyway for regular maintenance even if retrofitting is not conducted. Therefore, this amount of waste generation will not be reduced by retrofitting, so only construction waste from implementing retrofitting activities is counted in this study.

During the operation stage, the waste generated from operating, maintaining, repairing and replacing the upgraded building components or systems needs to be calculated. The weight of replaced building materials is relatively easy to estimate. For example, the weight of insulation materials of external walls can be estimated based on area of external walls (excluding area of windows), and density and designed thickness of required insulation materials. As for the replaced components of building service systems, they may be reusable or recyclable, such as the motors from replaced lifts, which will not be landfilled directly. Therefore, the waste generation by replacing them may not be accurately estimated in practice. Considering the small amount of waste generation by operating, maintaining and replacing the building service system, if the waste cannot be accurately estimated, it will be neglected in this study. However, post-assessment can be conducted to obtain real-time data about waste generation to calibrate the estimation results and can also be used as a reference for future study. Due to the time constraint, the post-assessment was not realised within the period of the thesis study. It may be conducted as a follow-up study to this research.

(4) Material use

The amount of reusable or recyclable materials is estimated for the retrofitting and operation stage. The higher the percentage of reusable or recyclable materials used in the retrofitting stage, the better the estimation result for material use. In the operation stage, the same type and quantities of materials are used for replacement when it is at the end of the service life of the building materials and/or systems. Therefore, the percentage of reusable or recyclable materials in the operation stage would be consistent as it is in the retrofitting stage.

(5) Initial cost, operation cost, maintenance cost, repair cost and replacement cost

LCC is used to assess the economic performance of potential retrofitting activities. In the conceptual model, the initial cost of materials and building systems in the retrofitting stage is counted. In the operation stage, the costs for the use of electricity and water for operating different electricity-related and water-related systems, for maintaining the building such as cleaning and facility management, and for repairing or replacing broken and obsolescent materials and components are included. In practice, the retrofitting team needs to conduct a statistical survey to obtain the initial cost, maintenance cost, repair cost and replacement cost for potential retrofitting activities. However, it is an ideal data collection method only when time and budget are not issues. Alternatively, the data collected through existing publicly available sources, such as research studies, reports and websites, can be adopted to approximately evaluate the economic performance of potential retrofitting activities.

As discussed in Section 4.3.1.4 of Chapter 4, EAC is calculated in this conceptual model to evaluate the economic performance of potential retrofitting activities. With the determined study period in the LCA study and collected costs by potential retrofitting activities, the EAC of them can be calculated based on Equation 4.3.

6.7.1.2. Evaluation of subjective criteria

The subjective criteria identified in this conceptual model are indoor environmental quality in the environmental dimension and all assessment criteria in the social dimension. Indoor environmental quality is a special criterion, which can be assessed using objective methods to quantify sensations (temperature, humidity, CO_2 concentration) or objective methods to measure how people feel or are satisfied with indoor environmental quality. Section 6.7.1.3

elaborates on how to assess indoor environmental quality using objective and subjective methods.

Assessment criteria in the social dimension are used to measure retrofitting activities' social impacts on people who use the building, or live or work in surrounding communities, and even the whole of society. As Table 6.2 shows, the impacts may be negative impacts on the retrofitting stage, including impacts on the health and comfort of people living or working in neighbouring buildings (S1-1 and S1-2 in Table 6.2), impacts on safety issues on the construction site (S2-1) and damage to cultural heritage (S3-1). Moreover, retrofitting activities may increase or decrease tenants' satisfaction with the use of the retrofitted building by increasing or decreasing accessibility to building facilities and services (S4-1 and S4-2) and imposing impacts on building maintenance (S5-1). As discussed in Section 4.4 of Chapter 4, SCBA and S-LCA are two common methods to assess social impacts.

SCBA is normally used to evaluate what the impact of an investment is on society, so it is often used by government to support decision making. However, the monetary-equivalent measure in SCBA is much critiqued since there is no agreement on attaching a price to welfare variation. S-LCA is another popular method to assess social impacts, which is compatible with the assessment framework in LCA. Since the environmental impacts are assessed by using LCA in the conceptual model, S-LCA is a more suitable method to assess social impacts caused by retrofitting activities compared to SCBA.

In S-LCA, a value score is used to express levels of measures on social impacts of retrofitting activities. Four common types of rating scales that use value scores to express measurements at different levels are summarised below (Bhattacherjee 2012; Dodgson et al. 2009; Hobbs & Meier 2000):

- Nominal scale: a nominal scale, also called a categorical scale, reflects the attributes of different categorical data like the gender of participants, religious affiliation, etc. A binary scale is a special nominal scale, which only allows two options like yes or no.
- Ordinal scale: is used to measure order-oriented data, such as ranking of students by their grades. The Likert scale is a prevalent ordinal scale that uses simply worded

statements to which respondents can express their level of agreement or disagreement on a three- four-, five-, six-, or seven-point scale.

- Interval scale: an internal scale where not only the order of different options but also the magnitude of difference between each level of options is calculable.
- Ratio scale: a scale with all the characteristics of nominal, ordinal and interval scales also has a “true zero” point, where the value zero denotes the lack or non-availability of the underlying construct.

All the social criteria from Table 6.2 are about the satisfaction level of stakeholders who use the building, visit the building, randomly pass by the building, or who work or live in neighbouring buildings. A rating scale acting as a proxy variable is commonly used to express different levels of social impacts (Ornaghi & Van Beveren 2011).

A study by Menadue (2014) aimed to determine whether green office buildings outperform conventional ones by conducting a survey to understand the different occupants’ satisfaction levels with building design and facilities of both green and non-green office buildings. A rating scale from 1 to 7 was adopted to express different levels of tenants’ satisfaction, where 7 represents “satisfactory” or “good”. Similarly, D’Oca et al. (2017) conducted a study to explore how social-psychological and demographic factors impact tenants’ behaviour and the intention of sharing the control system of buildings. A survey was also developed and sent to the targeted group – users of teaching buildings in universities across four countries, with a five-point Likert scale provided for respondents to use. In this way, the impacts of social-psychological and demographic factors can be measured.

A five-point Likert scale is also used in the conceptual model to estimate social impacts, as Table 6.4 shows. According to the developed social assessment criteria, the social impacts on the retrofitting stage are negative. Therefore, the less impact, the better the performance. For the social impact on the operation stage, the impacts from retrofitting activities are compared with the current situation before retrofitting is conducted. If it is same as the situation before retrofitting, a score of two should be given, representing the same performance level as the current situation. If the performance is better than the current situation, scores of three to five can be given based on the improved extent. If the performance is worse than the current situation, a score of one should be given.

Table 6.4. Rating scale for subjective issues

Impact range on retrofitting stage	Value score	Performance range in operation stage
Minimum impact	5	Excellent performance
Minor impact	4	Very good performance
Average impact	3	Good performance
Significant impact	2	Same as current performance
Very significant impact	1	Unsatisfactory performance

Source: Adapted from Vagias 2006

The final score for each assessment criterion is an average score of the value scores given by the retrofitting team, which can be achieved based on Equation 6.1.

$$S_{ij} = \frac{\sum S_{ij}^{n}}{n} \qquad \text{Equation 6.1.}$$

Where,

S_{ij} – social assessment score of retrofitting activity i regarding assessment criterion j

S_{ij}^{n} – the rating score of retrofitting activity i regarding assessment criterion j given by the nth assessor

n – the number of assessors in the retrofitting team

6.7.1.3. Evaluation of indoor environmental quality

Indoor environmental quality is a complicated issue involving various influential factors, such as the building’s insulation performance, tenants’ use behaviours, tenants’ age and gender etc., and different instruments may need to be used to assess different aspects of indoor environmental quality (Horr et al. 2016). Normally, an assessment of indoor environmental quality is conducted for two purposes. It can be conducted at the stage of designing and planning to identify improvement areas for which potential retrofitting activities can be proposed, which is called pre-assessment. Pre-assessment can also be conducted to evaluate effect by any changes on the indoor environmental condition – evaluating improvement of potential retrofitting activities. If it is conducted at the operation stage, the assessment is to measure the improvement by implementing retrofitting activities, or the level of satisfaction of occupants, which is called post-assessment. In this study, the conceptual model is developed to decide retrofitting strategies; thus, only pre-assessment is needed.

As discussed in Section 3.2.1 of Chapter 3, indoor environmental quality consists of three main components: indoor thermal quality, visual quality, and acoustic quality. The components can be expressed and assessed in either quantitative or qualitative ways (Cheong et al. 2020; Horr et al. 2016). For example, the thermal sensation is an objective item that can be quantified by evaluating indoor temperature, relative indoor humidity and CO_2 concentration. However, thermal comfort is a subjective issue about how occupants feel or are satisfied with indoor thermal condition (Horr et al. 2016; Kaushik et al. 2020). Similarly, either the sensation or comfort regarding the indoor visual quality and indoor acoustic quality can be evaluated.

(1) Quantitative assessment method

By implementing a quantitative method to evaluate indoor environmental quality, different simulation tools can be adopted to estimate the deviation of the current state from the required performance or improvement by any intervention (retrofitting activity). Based on the study by Wang and Zhai (2016) and Cheong et al. (2020), computation fluid dynamics (CFD) software has been extensively used to estimate indoor thermal quality. Commonly used simulation tools for estimating indoor visual quality include IESVE, SuperLite, Micro Lumen, Radiance, Lightscape, Daylight Visualizer Velux, Ecotect, and PKPM-daylight, and available simulation software tools for estimating indoor acoustic quality include Odeon, Epidaure, Soundplan, Raynoise, Ramsete, EASE, and Cadna. By using simulation-aided design methodology to estimate indoor environmental quality, three stages are commonly conducted: Step 1 – Model the indoor space in a virtual environment using modelling software, such as Sketchup and Autodesk CAD; Step 2 – Input the virtual model and indoor environmental quality-related factors in the simulation software, such as local climate, building orientation, HVAC arrangement, and lighting conditions; and Step 3 – Simulate indoor environmental quality performance based on the running results of the implemented simulation software (Cheong et al. 2020).

Different simulation tools can be used to assess specific parameters against the required performance. For example, the optimum temperature range for comfort in office buildings is from 21 ºC to 25 ºC based on the study by Kaushik et al. (2020). The natural sound level of a typical air conditioned office is between 45 dB and 70 dB (Horr et al. 2016). The recommended illuminance level of office buildings is 500 lux based on the Illuminating Engineering Society of North America (IESNA) standard (IESNA 2011; Park et al. 2021). The indoor environmental quality of office buildings is affected by various factors, which include but are not limited to work position, hours spent at work, clothing, physical activities and seating, posture and mental state, accessibility to indoor environmental quality controls, local climate and geography, and human factors such as age, gender and metabolism (Chen et al. 2021; Kaushik et al. 2020). Therefore, the benchmarks of indoor environmental quality differ by the location and work type of office buildings. The related local requirement or standard should be adopted as an assessment benchmark when applying the conceptual model to a specific retrofitting project.

(2) Qualitative assessment method

Since various factors affect indoor environmental quality, it is more suitable to express indoor environmental quality as a cumulative response of occupants toward the state of the indoor environment (Kaushik et al. 2020). Therefore, qualitative assessment methods are usually used to assess the level of comfort or satisfaction of occupants with indoor environmental conditions. A field survey can be used to collect opinions of occupants on the current state or changes in the physical environment via interviews and/or questionnaires (Horr et al. 2016). Interviews are intended for use in a detailed study with a small sample size, while a field survey can be used to obtain the perception of multiple occupants about indoor environment conditions through questionnaire surveys (Horr et al. 2016).

By collecting subjective opinions on indoor environmental quality, rating scales may be adopted to express different levels of satisfaction. For example, thermal comfort can be measured through the metric, the predicted mean vote (PMV), via a field survey (Cheong et al. 2020; Horr et al. 2016). The PMV predicts the mean response of building occupants based on the thermal sensation scale regulated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 (ASHRAE 2009; Che et al. 2019; Cheong et al. 2020; Horr et al. 2016). In ASHRAE, a seven-point scale ranging from -3 to +3, equating to cold and hot relative to the comfort optimum, is used to measure occupants' perception of indoor thermal conditions (Cheong et al. 2020; Horr et al. 2016). The Likert scale is also commonly used to measure the level of satisfaction of occupants for indoor environmental quality (Likert 1974). More discussion about rating scales can be found in Section 6.7.1.2.

There are also some survey instruments applicable for office buildings to conduct field surveys for measuring indoor comfort (Horr et al. 2016):

- BOSTI (Buffalo Organisation for Social and Technological Innovation)
- BUS (Building Use Studies Occupant Survey)
- HOPE (Health Optimization Protocol for Energy-efficient Buildings)
- REF (Ratings of Environmental Features)
- CWRE (Checklist of Work Related Experiences)
- AMA WorkWare (Alexi Marmot Associates)
- DQI (Design Quality Indicator)
- BASE (Building Assessment Survey and Evaluation)
- ProKlima
- ASHRAE RP-884
- CBE Survey (Centre for the Built Environment)
- OPN (Office Productivity Network)

(3) Combining quantitative and qualitative assessment methods

Quantitative and qualitative assessment methods can be conducted jointly to measure the indoor visual and acoustic environment of existing office buildings. For example, three simulation methods are available to simulate indoor visual condition: field lighting simulation, rendering-based lighting simulation, and immersive virtual simulation (IVS) (Ma, Lee & Cha 2022). Field lighting simulation is a traditional simulation method by changing the lighting conditions in a real office or mock-up rooms. Rendering-based lighting simulation is to investigate users' reaction to lighting by displaying rendered representations of the lighting designs of 3D computer models. IVS offers an immersive experience of one-to-one scale lighting designs of 3D computer models through visualisation devices such as head-mounted display and cave automatic virtual environment (Ma, Lee & Cha 2022). After experiencing the indoor visual conditions simulated by these three methods, occupants need to complete a field survey or interview to measure the impact on their visual perception and task performance (Cheong et al. 2020; Ma, Lee & Cha 2022). Similar simulation methods integrated with opinion collection methods, such as survey and interview, can also be used to assess indoor acoustic performance.

Based on the discussion above, multiple factors affect indoor environment quality, and both quantitative and qualitative methods are available for assessing indoor environment condition or estimating improvement by potential retrofitting activities. As a quantitative method, different simulation tools can be used to measure the state of indoor environment quality or improvement by potential retrofitting activities. However, it may be expensive and time-consuming to build virtual models.

In addition, there is no point measurement for indoor comfort, but a comfort zone for each factor (Horr et al. 2016). Either too high or too low measurement is not acceptable. However, even though the estimation results from using simulation tools fall in the comfort zone (benchmark), it cannot ensure that the occupants are satisfied with the condition of indoor environmental quality, since it is difficult to include all influential factors in the simulation process. Consequently, it will be less meaningful to include evaluation results of the improvement on indoor environmental quality by potential retrofitting activities to develop retrofitting strategies. Therefore, if time and budget are not problems, simulation methods may be conducted to estimate the improvement by potential retrofitting activities, but it would be better if the evaluation results from a qualitative assessment method can be combined to increase assessment accuracy. Otherwise, only a pre-assessment of indoor environmental quality to identify improvement areas for which potential retrofitting activities can be proposed is conducted in this study.

6.7.2. Weight assessment criteria

In most cases, assessment criteria in a decision-making process have different levels of importance representing a weighting. It is the value assigned to criteria which reflects preferences of decision makers and/or stakeholders among possible outcomes (Geneletti 2019). Different weighting generation methods can provide necessary frameworks for decision makers to compute weights. Delphi and Analytic Hierarchy Process (AHP) are two of the most prevalent methods for developing weights, especially in the context of group decision-making (Liu 2014).

The Delphi method engages experts to collect and distil judgments via an iterative process. The process stops only when the purpose of the study is reached, like theoretical saturation is reached, or group consensus is attained. The iterative process can refine and improve the reliability of the outcome (Skulmoski, Hartman & Krahn 2007). Zolghadr-Asli et al. (2021) stated that Delphi can help decision makers select the most relevant assessment criteria, and also assign proper weights to them. However, time and cost may hinder the applicability of this method (Liu, Ding & Samali 2013; Yu et al. 2015).

The other method, the AHP method, was developed by Saaty (1980), and mainly focuses on solving MCDM problems (Yu 2002). Decision makers need to give a rating score by pairwise comparison, which is used to calculate the weighting score (Steele et al. 2009). The rating scale adopted for the AHP is a nine-point scale, describing the relative importance level for pairwise comparisons. A matrix of pairwise comparison can be structured based on given rating scores, and weightings of assessment criteria are normalised values of the eigenvector that is related to the maximum eigenvalue for this matrix. Saaty (1980) explained that this determination process in AHP is the best way to reduce the impact of inconsistencies in the ratios.

AHP is recognised as a popular mathematically based trade-off technique. The formulation embodied can be used to construct and express trade-offs; eventually, it can assist in identifying the optimal solution (Kassab 2013). Moreover, the traits of the relatively low requirement on computation and the reliance on subjective assessment make AHP the most commonly used method for generating weights for evaluation criteria in MCDM (Zolghadr-Asli et al. 2021).

In this study, the conceptual model is developed based on MODM, which is one of the branches in MCDM. It is intended to consider trade-offs between the environmental, economic and social dimensions when using it to develop retrofitting strategies. Based on the above discussion, AHP is more suitable to be adopted in this study to estimate weights compared to Delphi. It is worthy to mention that there is a generalisation of AHP, Analytic Network Process (ANP), always discussed with AHP (Görener 2012). Both of them can be used to generate cardinal rankings of the alternatives, but ANP is usually adopted when the decision problems cannot be structured with a uni-directional hierarchical structure as they are in AHP (Görener 2012; Ossadnik, Schinke & Kaspar 2016). Since assessment criteria under each sustainability dimension have been identified as shown in Table 6.2 (see Section 6.6), they can be easily structured as a uni-hierarchical structure. Therefore, AHP is more suitable than ANP to be used in this study.

Two levels of weights need to be determined in this study. The first level is the three dimensions of sustainability: environmental, economic and social. The second level is assessment criteria under environmental and social dimensions. For assessment criteria under the economic dimension, based on the above discussion, the LCC method is used to calculate the EAC of potential retrofitting activities. In this method, the level of importance of these costs is regarded as equal. Therefore, no additional weighting is needed.

The AHP method should be conducted by a retrofitting team that has expertise in construction and property management. Meanwhile, they are playing a role in communicating with different stakeholders in the decision-making process in order to understand the needs of different stakeholders for building retrofitting. Ideally, different stakeholders or representatives of them can be included so that the determined weights can truly reflect the actual preference of different stakeholders. However, conducting an AHP study with too many people can be time-consuming and challenging.

6.7.3. Normalise measurements for criteria aggregation

Based on Section 6.7.1, assessment criteria are quantified into different units, which makes it difficult to have one final score to express overall performance. To solve the problem, normalisation is used to convert assessment results into a preference scale which is a unitless expression of the level of desirability of proposed retrofitting activities (Geneletti 2019).

6.7.3.1. Normalise measurements

The four most popular normalisation procedures (Equations 6.2–6.6) are introduced based on the study by Munier, Hontoria and Jiménez-Sáez (2019):

(1) Sum of performance values in a row:

$$a_{ij}^{*} = \frac{a_{ij}}{\sum_{1}^{n} a_{ij}} \qquad \text{Equation 6.2.}$$

Where,

a_{ij} – original performance value of option i under criterion j
a_{ij}^{*} – the normalised value of option i under criterion j
n – number of normalised values

(2) Largest value in a row:

$$a_{ij}^{*} = \frac{a_{ij}}{max_{a_{ij}}} \qquad \text{Equation 6.3.}$$

Where,

$max_{a_{ij}}$ – the largest performance value

(3) Euclidean formula:

$$a_{ij}^{*} = \frac{a_{ij}}{\sqrt{\sum_{1}^{n}(a_{ij})^2}} \qquad \text{Equation 6.4.}$$

It computes the formula in the denominator and divides each performance value by it.

(4) Maximum/minimum ratio:

$$a_{ij}^{*} = \frac{a_{ij} - min_{a_{ij}}}{max_{a_{ij}} - min_{a_{ij}}} \text{ if assessed performance is positive impact} \qquad \text{Equation 6.5.}$$

$$a_{ij}^{*} = \frac{max_{a_{ij}} - a_{ij}}{max_{a_{ij}} - min_{a_{ij}}} \text{ if assessed performance is negative impact} \qquad \text{Equation 6.6.}$$

Where,

$min_{a_{ij}}$ – the smallest performance value

Theoretically, the normalisation results by different methods should be the same (Munier, Hontoria & Jiménez-Sáez 2019). However, the last method (maximum/minimum ratio) is regarded as advantageous in MCDM since it incorporates subtracting members, which allows discrimination, while the first three produce a concentration of values. By favouring discrimination, the normalised results based on the maximum/minimum ratio can assist decision makers in distinguishing the optimal solution. In addition, the maximum/minimum ratio can ensure that the bigger normalised value can always represent better performance. In the assessment process of the conceptual model, both positive and negative impacts of retrofitting activities are evaluated. For positive impacts, a bigger evaluation score means better performance of the measured retrofitting activity. In contrast, a smaller evaluation score represents a better performance of the measured retrofitting activity if it causes negative impacts. With different evaluation directions, it is difficult to combine different assessment scores into one score to represent the overall performance. The normalisation method, maximum/minimum ratio, converts the negative direction to the positive by measuring the absolute distance between the evaluation and the target. In this way, a bigger normalised value is always desired to represent better performance. Due to the asserted benefits, the normalisation method, the maximum/minimum ratio (Equations 6.5 and 6.6), is adopted in the model to normalise evaluation values into a unitless scale.

6.7.3.2. Aggregate normalised measurements

The last task of this step is to aggregate normalised scores as one to express overall performance. The criteria aggregation is realised based on a rule that can combine assessment outcome and associated weights (Geneletti 2019). One of the most widely used rules for criteria aggregation is the weighted linear combination (WLC) (Steele et al. 2009). Moreover, this aggregation procedure permits "trade-offs" between criteria, in which poor performance regarding some requirements can be compensated by achieving better performance on other criteria (Geneletti 2019).

Trade-off is defined as the increased amount of one criterion while that of the value decreases regarding the other criterion in a particular solution (activity a_i in Equation 6.7) is replaced by another (a_j in Equation 6.7). Trade-off can be expressed as a ratio as in Equation 6.7 (Nowak 2010):

$$T_{ji}^{XY} = \frac{X_j - X_i}{Y_i - Y_j} \qquad \text{Equation 6.7.}$$

Where,

T_{ji}^{XY} – trade-off between a pair of criteria X and Y when activity a_i is replaced by activity a_j

$X_j - X_i$ – value increase in criterion X when activity a_i is replaced by activity a_j

$Y_i - Y_j$ – value decrease in criterion Y when activity a_i is replaced by the activity a_j

Nowak (2010) further explained Equation 6.7 by assuming a decision-making scenario that when analysing retrofitting activity a_i, it is realised that the evaluation for criterion X should be improved while the evaluation for criterion Y can be decreased. Therefore, there is no doubt that another retrofitting activity a_{j^*} is preferable if the evaluation $X_{j^*} > X_i$, and $Y_{j^*} \geq Y_i$. However, if the activity a_{j^*} does not exist, which is common in MCDM, Equation 6.7 can be used to look for activity a_j that can maximise the trade-off between criterion X and Y. The trade-off represented in Equation 6.7 is a point-to-point trade-off. In this study, the three pillars of sustainability – environmental, economic and social – are considered. Instead of the trade-off at a point, a range of acceptable trade-offs between the three pillars is more desired. The derivative of Equation 6.7 by considering trade-offs between the three sustainability dimensions is given in Appendix A.

In the weighted linear combination, the normalised criterion scores are multiplied by their weights, which then adds the results across all criteria to generate an overall score for each retrofitting activity (Geneletti 2019). It means that although a retrofitting activity is evaluated as poor performance regarding one or several assessment criteria, it is still possible to combine it with other retrofitting activities to form the optimal retrofitting strategy, which has the highest overall evaluation score, or maximised trade-off (at Step 6 in Section 6.8). In general words, the optimal retrofitting strategy is an amalgamation of retrofitting activities that can best use their strengths to complement others' weaknesses.

Based on the above discussion, weighted linear combination is adopted in this conceptual model to attain overall evaluation scores of proposed retrofitting activities. Based on Equation 6.8, the evaluation score of a retrofitting activity regarding one of the three sustainability dimensions can be attained by aggregating scores across all assessment criteria in this sustainability dimension.

$$P_j = \sum_{i=1}^{m} a_{ij}^{r} \times w_j^{r} + \sum_{i=1}^{n} a_{ij}^{o} \times w_j^{o} \qquad \text{Equation 6.8.}$$

Where,

P_j – the evaluation score of retrofitting activity j for one of the three sustainability dimensions

a_{ij}^{r} – the normalised score of retrofitting activity j regarding criterion i at the retrofitting stage

a_{ij}^{o} – the normalised score of retrofitting activity j regarding criterion i at the operation stage
w_j^r – the weighting score for criterion i at the retrofitting stage
w_j^o – the weighting score for criterion i at the operation stage
m – the number of assessment criteria included at the retrofitting stage
n – the number of assessment criteria included at the operation stage

By now, the contribution the proposed retrofitting activities can make to meeting retrofitting goals has been evaluated. It is time to consider whether there are other activities that may have better performance. If yes, they should be added. Therefore, the process goes back to the third step (Section 6.5) – propose retrofitting alternatives. In this way, the process can be refined more effectively compared to reacting to the feedback when the whole process is completed.

6.8. Develop retrofitting strategies

This step is to develop retrofitting strategies based on performance evaluation results of retrofitting activities. Rey (2004, p. 267) defined a retrofitting strategy as “a set of interventions, dictated by a coherent architectural attitude and technically optimised, in particular through a full coordination of the interventions on the sheathing surfaces and the technical installations”. Interventions refer to retrofitting activities in this study. Therefore, retrofitting strategy in this study can be defined as an amalgamation of retrofitting activities that can improve the performance of building envelopes and building service systems to achieve overall performance improvement of the existing building.

In this conceptual model, a binary linear mathematical model is established to determine which of the proposed retrofit activities should be adopted in order to achieve the highest overall evaluation scores while satisfying all project constraints. Before outlining the mathematical model, the concept of ceteris paribus is introduced. It forms the basis on which the performance of retrofitting strategies is evaluated.

6.8.1. Ceteris paribus

Ceteris paribus is a widely used assumption for analysing a series of impacts of a complex problem. It has been used as an important economic clause for a long time, meaning that the effect of an event is analysed in isolation and assuming that other factors remain constant

(Kremling, Bruns & Schildmann 2019). In this study, the concept of ceteris paribus is used to evaluate the performance of retrofitting strategies, which the assumptions below are based on:

(1) The effect of one single retrofitting activity is measured for each analysis.
(2) The effect of each retrofitting activity is analysed assuming that no other retrofitting activities have been implemented prior to this one.
(3) The effect of a retrofitting strategy is the aggregated effect of included retrofitting activities.

According to the three assumptions, the performance of a retrofitting strategy can be evaluated by aggregating the performance of contained retrofitting activities. However, there is an exception as discussed in Section 3.4.6 of Chapter 3. The performance of HVAC and the insulation of building envelopes are closely related, and improving building insulation should be prioritised over improving the energy efficiency of the HVAC system. Therefore, if both of them are proposed as retrofitting activities, the effect of improving HVAC should be superimposed on the effect of improving the insulation of building envelopes.

In summary, the concept of ceteris paribus is adopted not only to simplify evaluation but also to help make it clear how much benefit the retrofitting activity can bring, and how adverse an impact the activity can cause. Then, different activities can largely borrow others' strong points and offset weaknesses to develop a retrofitting strategy, reflecting "trade-offs" in the weighted linear combination discussed in Section 6.7.3.

6.8.2. A binary linear mathematical model for developing retrofitting strategies

Multiple objective programming is often represented as a mathematical model that coordinates different criteria to select the best element from a set of alternatives (Alinezhad & Khalili 2019). Three common methods of multiple objective programming are multiple linear objective programming (MLOP), multiple nonlinear objective programming (MNLOP), and goal programming (GP). MLOP should be adopted to achieve an optimal solution if all objective functions can be optimised. If some constraints or objective functions are not linear, which means not all objective functions can be optimised, MNLOP can be used to generate solutions that can “best” satisfy most of the objectives. As for GP, preferred solutions are developed instead of the optimal solution by minimising unwanted deviation variables (Romero 2001).

As discussed in Section 4.5.3 of Chapter 4, an optimal solution is desired for a retrofitting project, which means the developed retrofitting strategy can have the maximised overall evaluation score regarding the three sustainability dimensions within project constraints. In addition, the performance of retrofitting strategies is evaluated in a linear form, as Equation 6.9 shows. Therefore, MLOP is suitable to be adopted in the conceptual model to develop retrofitting strategies. However, there is a chance that no solution can be generated by using MLOP. In this case, other retrofitting activities that may better meet retrofitting goals should be proposed. Otherwise, some compromise has to be made to get the optimal solution, such as increasing the project budget.

To establish a linear mathematical model, three elements should be clarified (Vanderbei 2020):

- **Decision variables** are physical quantities that decision makers have control over. They are usually denoted as:

  $$x_j, j = 1,2, \dots, n$$

- **Objective functions** are mathematical functions of the decision variables that turn a solution into a numerical value. In linear programming, they are always used to maximise or minimise linear functions, which can be represented as:

  $$\text{Max/Min } Z = c_1x_1 + c_2x_2 + \cdots + c_nx_n$$

- **Constraints** are a set of functional equalities and/or inequalities that describe physical, economic, technological, legal, ethical, or other constraints with numerical values that can be assigned to decision variables. They can be represented as linear combinations of decision variables:

  $$a_1x_1 + a_2x_2 + \cdots + a_nx_n \begin{Bmatrix} \geq \\ = \\ \leq \end{Bmatrix} \text{b}$$

In this conceptual model, binary linear programming, a special branch of MLOP, is used to develop retrofitting strategies. In binary linear programming, each decision variable can only have a value of 0 or 1. It could refer to the rejection or acceptance of a choice, the turning off or on of switches, a no or yes response, or a variety of other scenarios (Chinneck 2004). In the conceptual model, 0 represents that the proposed retrofitting activity is not selected, and 1 represents that the retrofitting activity is selected and will be amalgamated with other selected activities as a retrofitting strategy.

In MLOP, two common approaches are used to deal with conflicts between different objectives (Benayoun et al. 1971). The first approach is to define a hierarchy for objectives that represents an order of achievement according to the project goals. It regulates that the second objective can only be reached with the precondition that the first one has been reached, and so on. The second approach uses "utility" in which each objective function is assigned a weight w, then a unique objective function Z= $\sum_j w_j c_j$ can be maximised or minimised.

In this conceptual model, the "utility" method is adopted, since the direction of projections can be determined by integrating weights in MLOP (Joro, Korhonen & Wallenius 1998). By determining weights, decision makers can directly or indirectly influence decision outcomes that reflect their preference structure. In addition, integrating weights in the evaluation also complies with the form of a weighted linear combination, representing trade-offs between different objectives (see Section 6.7.3).

Based on the above discussion, the problem of developing an optimal retrofitting strategy for getting the best environmental, economic and social performance within project constraints can be put in the form:

- The objective function has the form maximise $Z = \sum_{j=1}^{n} c_j x_j$ which indicates the expectation of better sustainability performance.
- All of the x_j where $j = 1,2,\ldots,n$ are binary values (can only have the value 0 or 1).
- Weight w for each sustainability dimension is combined into the objective function to represent a "trade-off" between the three sustainability dimensions (see discussion in Section 6.7.3).

- If a specific solution region can be defined to satisfy a retrofitting goal, such as a retrofitting goal to achieve at least 30% energy saving, it should be formulated as a constraint function in the "subject to" bracket as: $\sum_{j=1} a_j x_j \geq 30\%$ (where a_j represents the energy saving ability of each proposed retrofitting activity). In this way, it can ensure that the generated retrofitting strategy can reach this retrofitting goal.

By combining the above elements, the binary linear mathematical model for developing retrofitting strategies can be built as Equation 6.9.

$$max\, Z = W_{en} \times \sum_{j=1}^{n} P_j^{en}\, x_j + W_{ec} \times \sum_{j=1}^{n} P_j^{ec}\, x_j + W_s \times \sum_{j=1}^{n} P_j^{s}\, x_j \quad \text{Equation 6.9.}$$

$$s.t. \begin{cases} \sum\limits_{j=1} a_{1j} x_j \geq (=, \leq) b_1 \\ \sum\limits_{j=1} a_{2j} x_j \geq (=, \leq) b_2 \\ \qquad \vdots \\ \sum\limits_{j=1} a_{mj} x_j \geq (=, \leq) b_m \\ x_j = 0,1 (j = 1,2, \dots, n) \end{cases}$$

Where,

Z – the overall performance of a retrofitting strategy
W_{en} – the weighting score of the environmental dimension
W_{ec} – the weighting score of the economic dimension
W_s – the weighting score of the social dimension
P_j^{en} – the evaluation score of retrofitting activity j in the environmental dimension, which can be calculated based on Equation 6.8
P_j^{ec} – the evaluation score of retrofitting activity j in the economic dimension, which can be calculated based on Equation 6.8
P_j^{s} – the evaluation score of retrofitting activity j in the social dimension, which can be calculated based on Equation 6.8
$\sum_{i=1} a_{mj} x_i \geq (=, \leq) b_m$ – the constraint function for subjecting to project constraint b_m
n – the number of proposed retrofitting activities
m – the number of project constraints
$x_j = 0,1$ – whether retrofitting activity x_j is selected. When $x_j = 0$, it is not selected. When $x_j = 1$, it is selected.

Based on Equation 6.9, the retrofitting activities that can be aggregated as a retrofitting strategy with the maximised overall evaluation score while satisfying project constraints can be identified (denoted as 1). In this way, the optimal retrofitting strategy within project constraints can be developed.

However, with multiple assessment dimensions, criteria and objectives involved, the calculation of Equation 6.9 is very complex and time-consuming. To solve this problem, computer programming, such as Excel and MATLAB, can be adopted to calculate the mathematical model.

6.9. Conduct sensitivity analysis

There is no doubt that most decisions are affected by uncertainties, which may be caused by measurement and conceptual errors, limited knowledge about process, simplification and data scarcity, different values and opinions, and the future (Geneletti 2019). Sensitivity analysis can be conducted to test how, and how much, those uncertainties affect the results (Saltelli et al. 2019). Sensitivity analysis can help develop better monitoring strategies and experiment designs by, for instance, highlighting the significance and amount of data to be collected (Douglas-Smith et al. 2020). In addition, by identifying parameters that may be “insensitive’ or “inactive”, sensitivity analysis can also help limit the parameter space to those affecting model outcomes only marginally or not at all (Douglas-Smith et al. 2020). In particular, in the context of building performance evaluation, sensitivity analysis can be used to identify significant and negligible parameters in a building energy model to indicate the possibility of simplifying, optimising, calibrating or correcting the model (Pang et al. 2020).

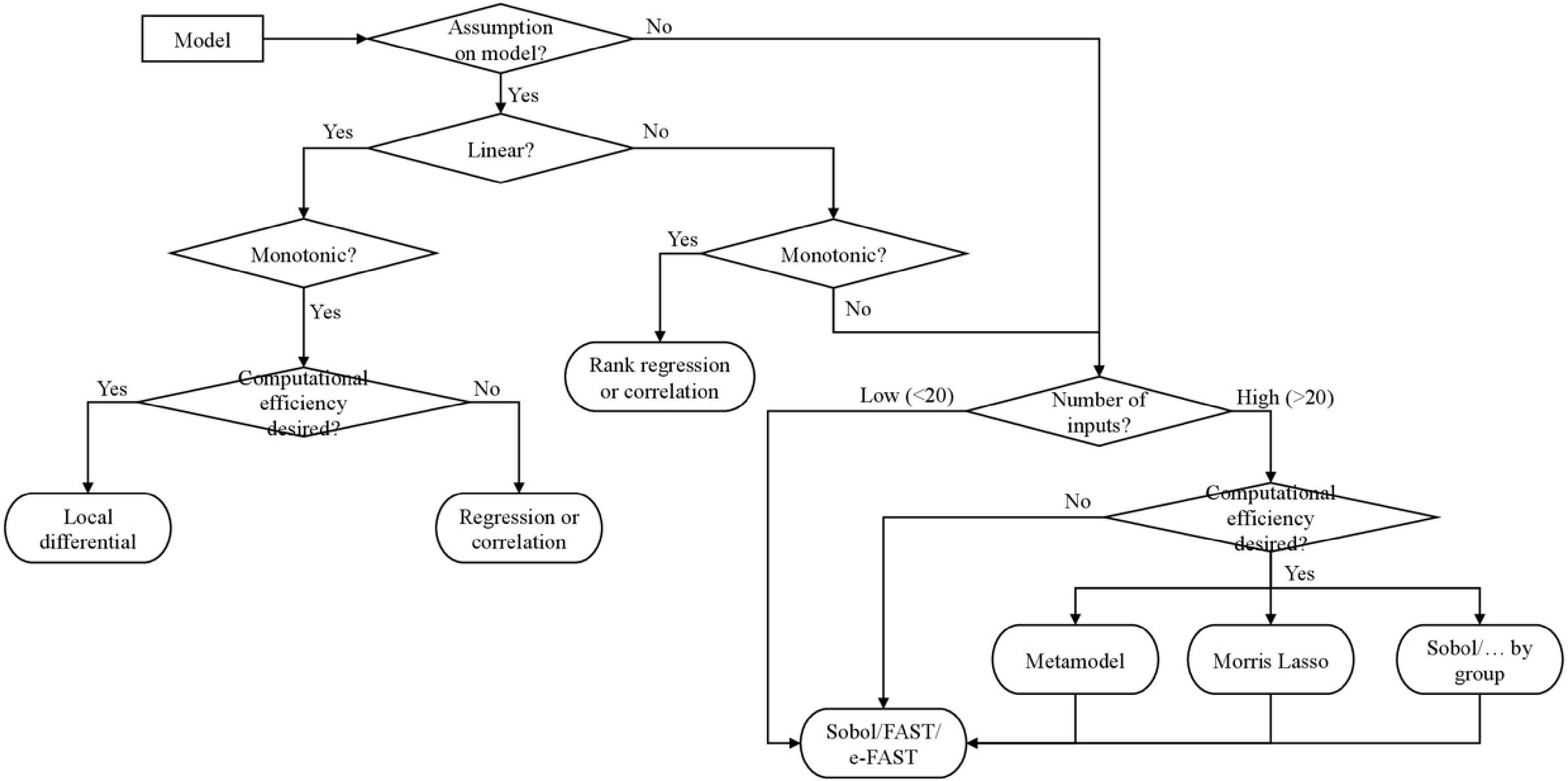
Many sensitivity analysis methods are available and can be selected according to the traits of the given problems and available computational resources (Pang et al. 2020). The common sensitivity analysis methods and their pros and cons are listed in Table 6.5. Based on the specific situation of the implemented model and the characteristics of different sensitivity analysis methods, a suitable one can be selected referring to Table 6.5 and Figure 6.4.

Table 6.5. Pros and cons of common sensitivity analysis methods

Method	Pros	Cons
Local	• Easy to understand and implement • Computationally efficient	• Not suitable when the model is nonlinear or nonmonotonic • Parameters cannot be varied simultaneously • Does not support uncertainty analysis
Morris	• Computationally efficient and robust • Produces results comparable to computationally expensive methods like the Sobol method and the FAST method	• Not the most robust method • Not able to quantify the individual interaction between two parameters • Does not support self-verification
PEAR, SRC	• Easy to understand and implement • Computationally efficient	• Not robust • Only suitable for linear and monotonic models
PCC	• Easy to understand and implement • Computationally efficient • Parameter interaction is eliminated (PCC)	• Not robust • Only suitable for linear and monotonic models
SPEA, SRRC	• Easy to understand and implement • Computationally efficient • Suitable for nonmonotonic models	• Not robust • Only applied to monotonic models
PRCC	• Easy to understand and implement • Computationally efficient • Suitable for nonmonotonic models • Parameter interaction is eliminated	• Not robust • Only applied to monotonic models
Sobol	• Most robust • The results often serve as a benchmark for the testing of other sensitivity analysis methods • Provide high-order interactions	• Lower computational efficiency compared with the GAST/e-FAST method
FAST	• Model-independent • The variance of the outputs can be apportioned to the inputs • Computationally efficient compared with Sobol	• Computationally complex for a large number of inputs • Cannot address high-order interactions (e-FAST can solve this problem) • The result is not as robust as that of Sobol
Metamodel	• A potentially computationally intensive model can be simplified to a mathematical model • The coefficients of the model may indicate sensitivities directly	• The calculation to generate a metamodel can be resource intensive • The valid domain and applicability of the model are highly dependent on the training data
RSA	• Computationally efficient	• Cannot quantify the interactions among input parameters
Lasso	• Computationally efficient • Can be used as a screening technique	• Cannot generate robust results

Source: Pang et al. 2020

Figure 6.4. Decision diagram to guide the selection of sensitivity analysis methods



Source: de Rocquigny, Devictor & Tarantola 2008; Pang et al. 2020

Based on the discussion in Section 6.8, the established mathematical model in this study is a linear model. Moreover, by using the normalisation method, maximum/minimum ratio, the direction of assessment is the same: the bigger the estimation score, the better the performance of potential retrofitting activities. Therefore, the model is monotonic. According to Figure 6.4, the sensitivity analysis method, local differential or regression/correlation, may be selected for a linear, monotonic model, but local differential can bring a more efficient analysis process. Therefore, local differential is adopted in this study for the sensitivity analysis.

The local sensitivity analysis method often computes the derivative of the model at a given point or the average derivative of several points in the parameter space to assess the significance of an input parameter (Douglas-Smith et al. 2020; Pang et al. 2020). By using the local sensitivity analysis method, only one parameter is changed at a time while other input parameters are fixed; thus, it is also known as One-At-a-Time (OAT) (Pang et al. 2020; Saltelli et al. 2019). There are various methods for determining how much a parameter should be perturbed, but the most frequently used one is to employ a proportional increment (Razavi & Gupta 2015). For example, a parameter might be increased or decreased by 10% of its nominal value up to and including a specified bound. Ding (2005) developed a multi-criteria approach for measuring the performance of sustainability, and three different discount rates, 5%, 10%, and 15%, were used for calculating the NPV of three operations as a sensitivity analysis of the study. The result showed that with a discount rate of 5%, all three options are acceptable, while all of them are unacceptable with a discount rate of 15%. Only one option is acceptable with the 10% discount rate.

As discussed in Section 4.3 of Chapter 4, uncertainty in this study is mainly from the selection of discount rate, study period and coefficient. Therefore, sensitivity analysis can be conducted by replacing the values with other possibilities to test the stability of the results. Based on the results of the sensitivity analysis, if any component should be refined, the process should be repeated from the modified step. Otherwise, the process can proceed to the next step.

6.10. Choose the “best” solution

By following the previous seven steps, an optimal retrofitting strategy for best improving environmental, economic and social performance within the current project constraints can be developed. However, decision makers may prefer more options from which the one that "best" satisfies their demands can be selected. It can be realised by relaxing or tightening one or several project constraints so that the optimal retrofitting strategies regarding the changed project constraints can be obtained accordingly. For example, the retrofitting goal is to have at least a 30% energy saving. Following the above seven steps, an optimal retrofitting strategy is developed, which can save 32% of energy. However, by relaxing the project constraint, for example, increasing the budget by 5%, the retrofitting strategy developed with the relaxed project constraint can have a 50% energy saving. Then, the building owners or investors can decide if they would like to pay 5% more to get an additional 18% in energy saving.

With several retrofitting strategies developed, the retrofitting team is responsible for explaining to building owners or investors how the strategies meet retrofitting goals and objectives with different project constraints. They should also provide suggestions on the "best" solution based on their expertise and experience. With the given suggestions and uncertainty involved, the final decision makers, usually building owners or investors, can simply select the one that can primarily meet their requirements as the "best" solution.

6.11. Summary

This chapter developed a conceptual model for deciding retrofitting strategies by considering essential elements in MODM and the required steps for developing retrofitting strategies. There are eight steps in the conceptual model, which can be followed to develop an optimal retrofitting strategy that can maximise improvement on environmental, economic and social dimensions within project constraints.

Following the illustration of the conceptual model, each step included is elaborated. The first step is to set retrofitting goals and objectives based on communication with different stakeholders and consideration of project constraints. Then, the retrofitting team needs to conduct a building audit to identify the problems the building has. The third step is to propose retrofitting activities that may solve the identified problems.

The fourth step is to develop assessment criteria for measuring the achievement of retrofitting goals and considering the three pillars of sustainability. With developed assessment criteria, the retrofitting team can evaluate the ability of proposed retrofitting activities to reach retrofitting goals. Moreover, the environmental, economic and social impacts of these activities can also be measured. In this step, the measurement of retrofitting activities' performance is normalised to unitless so that they can be aggregated to one measure to show overall performance. Meanwhile, a weighting system by AHP is combined to represent different importance levels among assessment criteria and the three sustainability dimensions.

With the evaluation results of the performance of potential retrofitting activities, retrofitting strategies can be developed based on an MLOP mathematical model established in Step 6. The developed strategy has the highest overall score, indicating the maximised improvement in environmental, economic and social dimensions within project constraints. The next step is to conduct a sensitivity analysis to test how, and how much, uncertainty affects the results. Based on the results of the sensitivity analysis, if no components need to be refined, the decision process can go to the final step – the "best" solution is chosen by building owners or investors.

Since the developed model is a conceptual model, which is intended to be general, the framework of the model can be adapted for any retrofitting project. Therefore, the conceptual model needs to be converted to an operating model before applying it to a real case. The next chapter explains how the conceptual model can be converted to an operating model, and the process is illustrated in a case study.

Chapter 7. Case study – Data collection

7.1. Introduction

The last chapter developed a conceptual model for deciding retrofitting strategies for office buildings. A conceptual model is general and can be adapted to suit the specific situation of any retrofitting project. Therefore, the conceptual model needs to be converted to an operating model before applying it to an actual retrofitting project. To validate the model for developing retrofitting strategies, a case study, which is retrofitting an office building in Hangzhou city, Zhejiang province, China, is conducted. The case study has two parts. The first part collects data about suitable retrofitting activities and assessment criteria in China, which can be used to convert the conceptual model to an operating model for the Chinese retrofitting market. The second part quantifies the operating model by applying it to develop retrofitting strategies for the case building, illustrated in the next chapter.

This chapter focuses on the first part of the case study. First, the rationale behind the case study is discussed (Section 7.2). The background information about the case building is presented (Section 7.3). Then, a two-stage process of data collection for the case study is demonstrated (Section 7.4 and Section 7.5). The first stage is to collect broad information about sustainable retrofitting in China by a survey with professionals and stakeholders of retrofitting. In stage two, focus group discussions are conducted with same types of participants of the survey to consolidate the result of the survey and further modify retrofitting activities and assessment criteria to be suitable for use in the case study and other retrofitting projects in China. Focus group discussions are also conducted to estimate weights of the three sustainability dimensions and assessment criteria.

7.2. Rationale behind the case study

A case study was selected to demonstrate the process of using the conceptual model to develop retrofitting strategies for an actual office building. When using a case study approach to describe steps undertaken, it allows the researcher to break down a complex and broad topic, or phenomenon, into manageable research questions (Heale & Twycross 2018). For example, by conducting the case study, the process from modifying retrofitting activities and assessment criteria to deal with location variations, to developing retrofitting strategies for the case building by taking steps in the conceptual model (Figure 6.2 in Chapter 6), can be illustrated, the methods to assess environmental, economic and social performance of retrofitting activities can be described, and the way to develop retrofitting strategies by balancing the three sustainability dimensions can be explained.

A single case study or a multiple case study can be conducted to reach an illustrative or verifiable conclusion (Gustafsson 2017). A multiple case study is usually conducted to understand the differences and similarities between different cases (Gustafsson 2017; Heale & Twycross 2018), while a single case study is an ideal option if the researcher only wants to look at one aspect (for instance, one person from a particular group) or one group (for example, a group of people) (Yin 2009). In this study, a single case study was conducted to illustrate the process of using the conceptual model to develop retrofitting strategies for an office building. There is no doubt that conducting more case studies can increase the validity of the developed conceptual model. The validity in this study means that by using the developed model, retrofitting strategies can be developed for an existing office building, and the potential improvement from the developed retrofitting strategies can be estimated, and this can be done with a single case study. The case study is also conducted to illustrate how to use the conceptual model to develop retrofitting strategies for an existing office building by considering the environmental, economic and social dimensions. It is a complex process, so it is important to provide a clear and detailed presentation of the process, such as collecting both quantitative and qualitative data, assessing performance of retrofitting activities in the three sustainability dimensions, and establishing the mathematical model and running it in a program for developing retrofitting strategies. Studying only one case allows the researcher to deliver a more careful study, contributing to a deeper understanding of the subject (Gustafsson 2017) – improving the environmental, economic and social performance of existing office buildings by retrofitting.

7.3. Background information for the case study

The case building is in Hangzhou city, Zhejiang province, China. Based on Zhejiang Statistical Yearbook (ZPBS & SOTNBS 2021), the average temperature in Hangzhou is 28 ˚C in summer and 8 ˚C in winter in 2021. The average relative humidity ranges from 76% to 81%. To maintain a comfortable indoor environment, buildings in Hangzhou city often have high operation costs, energy consumption, and carbon emissions.

Zhejiang province is ranked fourth in GDP in the country, and has a relatively fast development and acceptance of green buildings (Ge et al. 2018). However, based on the national green building standard, Assessment Standard for Green Building (ASGB) (BG/T 50378-2014), only 276 buildings were granted green building labels in Zhejiang province in 2016. The national standard regulates green buildings at two stages: the design label at the building construction stage, and the operation label when the building is in use (MOHURD 2014). Of the 276 green buildings, only 20 have been given operation labels. Moreover, only 79 of the labelled projects can reach the requirements of operation management due to insufficient supervision by building owners and facility managers (Shen, Zhao & Ge 2020).

The case building is an office building located in the centre of Hangzhou city. The building was built in 1985 and is a relatively old office building in Hangzhou city. The building's total floor area (the sum of the horizontal projected areas of each floor of the building) is about 19,683 m^2, and it has a land area of 2,386 m^2. The building has 13 storeys, and no basement. In China, public buildings are designed for people for a variety of public activities, and an office building is one type of public building (Wei & He 2017). Characteristics of the case building are summarised in Table 7.1.

Table 7.1. Characteristics of the case building

Age	37 years
Total floor area	19,683 m^2
No. of storeys	13
Height	42.7 m
Category of public buildings[1]	Level II
Shape factor[2]	0.22
Structure type	Frame-shear wall structure
Glazing type	Single glazing
Area ratio of window to wall	East: 0.19
	West: 0.26
	South: 0.29
	North: 0.20
Average annual energy consumption	1,836,262 kWh
Average annual energy consumption per floor area	93.29 kWh/m^2
Average annual CO_2 emissions	1,830,753 kg CO_2
Average annual CO_2 emissions per floor area	93.01 kg CO_2/m^2
Average annual water consumption	23,970 kL
Average water consumption per floor area	1.22 kL/m^2

Note:

1. Public buildings in Zhejiang Province can be grouped into three categories based on the local standard, Design Standard for Energy Efficiency of Public Buildings (UAD, ZIAD & CMA 2007):
   - Category I: A public building with a building area greater than or equal to 20,000 m^2, or with a full air conditioning system fully equipped.
   - Category II: A public building with a building area of less than 20,000 m^2 and without or partially equipped with air conditioning systems.
   - Category III: A public building where the building is out of use during the summer and winter months of the year when the cooling and heating loads are at their peak, and where no air conditioning is provided.
2. Shape factor refers to the ratio of the exterior area of a building in contact with the outdoor atmosphere to the volume it encloses.

Hangzhou is in the hot-summer-cool-winter climate zone where air conditioners or heaters are the heating supply. A reverse cycle air conditioning system was installed five years ago for cooling in summer and heating in winter, and the HVAC system can cover at least two-thirds of the area of the building, with the remaining one-third naturally ventilated. Before that, fans and heaters were used to adjust indoor temperature. Usually, in this climate zone, the cooling period (summer) is from June to September and the heating period (winter) is from December to February. The indoor environment is good enough during spring and autumn, and no intervention (HVAC or fans) is needed. Since the building was built, some upgrades have been undertaken from time to time when the building owner realised there was a problem or due to demand by tenants. Upgrades include the newly installed reverse cycle air conditioning system and changing some steel window frames to PVC frames. No planned and comprehensive retrofitting has ever been conducted on the building.

7.4. Data collection strategy for the case study

The case study is conducted to demonstrate how to use the conceptual model to develop retrofitting strategies for an office building. The information in the conceptual model is intended to be general, which may not be applicable to the case building. To deal with locational variations, the conceptual model needs to be converted to an operating model by modifying retrofitting activities and assessment criteria to suit the local situation. As discussed in Section 5.3.2.1 of Chapter 5, many data collection methods are available to gather people's opinions, such as surveys, interviews and focus groups. In this case study, an explanatory sequential strategy is adopted to collect data in two stages from the broad to the specific.

In stage one, a survey was conducted to collect opinions about retrofitting activities and assessment criteria of sustainable retrofitting from professionals and key stakeholders of retrofitting in northern and southern China. The survey can help gather opinions about sustainable retrofitting in China in a relatively short time. However, the collected information tends to be broad and general. In stage two, more detailed data is collected to consolidate the results of the survey and further modify the retrofitting activities and assessment criteria to be suitable for local use. In this case study, three focus group discussions were conducted with local professionals. Focus group discussion is a suitable method when the purpose of data collection is to build a holistic understanding of the problem situation based on participants' comments and experiences (Bhattacherjee 2012). Hearing others speak often prompts responses or ideas that participants have not considered previously, which provides chances for an in-depth examination of complex issues (Bhattacherjee 2012), such as how to balance the improvement in the three sustainability dimensions, how important different stakeholders consider each sustainability dimension to be and why, etc. However, the findings may not be generalised to other settings because of the small sample size (Bhattacherjee 2012). Therefore, if using the conceptual model in other locations, focus group discussion or other forms of data collection need to be conducted with local professionals to make sure the model is modified to comply with the local situation. The details of each adopted method in this case study are discussed in the following sections.

7.4.1. Stage 1 – Questionnaire survey

In the first stage of data collection for the case study, a questionnaire survey was conducted to collect general opinions on suitable retrofitting activities and assessment criteria for retrofitting office buildings in China. Opinions about the development of sustainable buildings and the trend of retrofitting were also collected.

7.4.1.1. Development of the questionnaire survey

The questionnaire was designed in four parts with 17 questions based on the literature review. Both closed and open-ended questions were created to gather respondents' attitudes and opinions about sustainable retrofitting and their working and life experiences about retrofitting. The four parts of the questionnaire are explained below.

Part I: General information

This part had seven questions on some basic information about respondents like gender, age and experience of retrofitting. Different roles in retrofitting projects have different requirements, and respondents' experience and background can influence their answers. Therefore, respondents' background information can be used to analyse possible reasons for the provided answers. Other questions included how many retrofitting projects respondents have ever undertaken, and what kinds of buildings they have ever retrofitted to know whether they have experience in retrofitting office buildings.

Part II: Understanding about sustainable retrofitting

This part had four questions to capture the general understanding of sustainable retrofitting. Based on respondents' retrofitting-related experience, they were asked to give their opinions on "what" are common retrofitting activities and assessment tools that they ever used, "who" is responsible for improving sustainability, and "what" are drivers of retrofitting of buildings.

Part III: Level of importance of different aspects of sustainability

This part had three questions where respondents needed to give rating scores on different aspects of sustainability and the identified assessment criteria under environmental and social dimensions. Apart from the identified criteria in the survey, respondents were also able to provide other criteria that they think should be included in this study by asking about "others".

Part IV: Further discussion about improvement of sustainable retrofitting

This part had three open-ended questions for further discussion on "what" can be improved by sustainable retrofitting and "how" to improve the sustainable performance of existing buildings. Even though the survey always allowed respondents to give their own opinions by asking "other" after most of the questions, respondents could still share more opinions in this part to help analyse the provided data and explain the results. In addition, the last question asked what other actions can be taken to improve the performance of existing buildings which can be used to estimate future trends of retrofitting.

7.4.1.2. Pilot study

Before the main survey, a pilot study took place in December 2018 for about two weeks with three Australians and two Chinese professionals whose study fields are relevant to the built environment. The purpose of the pilot study was to verify whether the content was clear and easy to understand, whether respondents could answer questions in a proper way, and how long it would take to complete the survey. Based on their feedback in the pilot study, the questionnaire form was revised and refined until it was ready to send out for the main survey.

Respondents' feedback showed that it took about 10 to 15 minutes to finish the survey. Generally, the questions were clear and easy to understand, but there were still some vague expressions, including Question 3 (see Appendix B-2), it should be "property management industry" instead of "industry of building construction"; and the question "what do you expect to be improved by sustainable retrofitting" should be asked of professionals, building owners and tenants separately to identify gaps between provided services and requirements. Therefore, this question was split into two questions, Question 15 for building owners and tenants and Question 16 for professionals. After revising the survey based on these professionals' comments, the survey was finalised (see Appendix B-2).

The survey was designed to be conducted with professionals and key stakeholders of retrofitting in China, so the finalised questionnaire form was translated into Chinese. The translated questionnaire form was sent to the same two Chinese professionals who participated in the pilot study to check whether the translation distorted any questions. Their feedback showed that the meaning of the translated questionnaire form was consistent with the English version. The English version is in Appendix B-2 and the Chinese version is in Appendix B-3.

7.4.1.3. Sampling method and participant recruitment

Two sampling methods can be used to recruit respondents to a study: probability sampling and non-probability sampling methods (Sedgwick 2013). In the probability sampling method, each object has an equal chance to be selected as a sample, and researchers' opinions do not influence who is selected in this method. If the sample size is big enough, it is likely to be representative of the whole population so that findings generated based on the analysis of the sample can be considered representative of the whole population (Naderifar, Goli & Ghaljaie 2017). The common probability sampling techniques are simple random, stratified random, random cluster, and systematic sampling. They are often used to collect data in quantitative research (Naderifar, Goli & Ghaljaie 2017).

Non-probability sampling methods are usually used in qualitative research (Naderifar, Goli & Ghaljaie 2017). In contrast to probability sampling, not everyone has an equal chance of being selected as the sample in these sampling methods. Usually, samples are selected because they are available to researchers. In this sampling method, whether the selected samples can represent the whole population is unclear. As a result, the sampling rate in error cannot be calculated (Naderifar, Goli & Ghaljaie 2017). Common non-probability sampling methods include convenience, purposeful and quota sampling.

One method of convenience sampling is called snowball sampling as the sample size gets bigger over this sampling method, just like rolling a snowball (Cohen & Arieli 2011). Snowball sampling is a respondent-driven sampling method, also called chain-referred or link-tracing sampling (von der Fehr, Sølberg & Bruun 2018). By using snowball sampling, researchers typically begin with a small number of initial contacts who meet the research criteria and are invited to participate in the study. The respondents are then asked to recommend other contacts who meet the research criteria and may be willing respondents as well, who in turn recommend other potential respondents, and so on (Parker, Scott & Geddes 2019). It allows researchers to reach a population that is difficult to sample when using probability methods (Naderifar, Goli & Ghaljaie 2017).

Snowball sampling is believed to be simple and cost-efficient with little planning and fewer resources needed (Dudovskiy 2016). This sampling method also allows researchers to communicate better with respondents because subsequent respondents are acquaintances of the first participant who is linked with researchers (Naderifar, Goli & Ghaljaie 2017). The sampling process often ends when a research saturation point is reached, such as until no more significant information can be offered from further sampling (Geddes, Parker & Scott 2018). However, there are some disadvantages to using this sampling method. Geddes, Parker and Scott (2018) stated that researchers have little control over the snowball sampling method since the subsequent selections mainly rely on previous contacts. Therefore, the selection of initial contacts is very important for guaranteeing the sample quality. Moreover, there may be sampling bias generated by snowball sampling. Referrals by previous respondents are normally to people they know well and they may be from the same group and share similar opinions.

There are three patterns of snowball sampling (Dudovskiy 2016):

- Linear snowball sampling: The sampling process starts with one subject, and the subject provides only one referral. This pattern is continued until the sample group is fully formed.
- Exponential non-discriminative snowball sampling: Multiple referrals are provided by the first subject recruited. This pattern is continued until sufficient primary data from the identified samples is collected.
- Exponential discriminative snowball sampling: Subjects give multiple referrals, but only one new subject can be recruited each time. The determination of a new subject is guided by the aim and objectives of the study.

This case study adopted the exponential non-discriminative snowball sampling method to quickly collect opinions about suitable retrofitting activities and assessment criteria in northern and southern China. China is divided into the north and the south by the Qinling Mountains–

Huaihe River Line, which is also a dividing line between warm temperate and subtropical climate zones in China (Xu et al. 2021). Therefore, the north and the south in China have different natural conditions and sociocultural customs. For example, due to historical energy scarcity and relevant heating standards, central heating is only available in the north for varying lengths of time. In the south, no district heating substations and long-distance heating pipelines have ever been provided (Yan et al. 2019). As a result of economic development over the past decades people who do not have access to central heating have begun to use air conditioners or heaters. Li et al. (2018) found that, apart from office buildings built before the 1980s that have different cooling and heating facilities such as fans and central heating supply, office buildings built after the 1980s are air conditioned across the whole country. It means that office buildings are similar in their heating and cooling source. In the north, HVAC is mainly used as a heating source for office buildings, while it is mainly used to cool down the indoor temperature in summer for office buildings in the south (Wang et al. 2020). Therefore, even though China is a big country with various climate conditions, the office buildings across the country have a similar way of operating and it is a good opportunity to test the flexibility of the conceptual model.

To understand the opinions of different roles in retrofitting projects, six groups of stakeholders were included in the survey: architects, engineers, project managers, facility managers, building owners, and tenants. To avoid the bias mentioned above, instead of one initial subject recruited, 24 initial respondents who were suggested to be active in the industry by scholars from two universities in China[1], and they were recruited in northern China (12 respondents) and southern China (12 respondents).

7.4.1.4. Survey process

The survey was conducted from January to March 2019 via the online survey tool SurveyStar. The survey link to the final survey was sent to the 24 initial respondents via WeChat, a commonly used communication tool in China. The respondents were invited to complete the questionnaire form and send the link to other people they thought were eligible for this study. A reminder was sent to them once a month for three months to make sure they had received the survey link and to remind them to send the link to other potential respondents. The information sheet and consent form were attached to th1e questionnaire form (the details are

Note 1: The two universities are Xi’an University of Architecture and Technology in the north, and Zhejiang University City College in the south.

in Appendix B-1). Any referrals could also read and determine for themselves whether they were eligible for this study.

The online survey can set whether a question is compulsory so that only completed surveys can be successfully submitted. Therefore, it is not possible to receive a form with missing answers. The only reason for invalid submission is that the respondent does not fit in any of the six roles identified in the questionnaire. By screening the role of respondents, 13 of the collected responses were not valid. Therefore, the final sample size of this study was 128.

Since the snowball sampling method was used, it is not known whether the sample size was representative. To consolidate the outcome of the questionnaire survey and further specify the model to be operational for the case building and other office buildings in China, three focus group discussions were organised with professionals in Hangzhou, as discussed in Section 7.3.2.

7.4.1.5. Survey analysis

a) Background of respondents

The background characteristics of respondents, including gender, age range, location and experience about building retrofitting, were investigated first since respondents' backgrounds can help explain the survey results. Table 7.2 shows, among all respondents, 66 were male and 62 were female. The role group of engineers was the largest group of respondents, representing 21.1% of all respondents. The number of respondents in each of the other five role groups was similar, at around 15% in each group. Generally, the distribution of role groups and genders can be considered balanced.

Table 7.2. Respondents in different roles by gender (128 responses)

Roles	Male	Female	Sub-total	% of total
Architects	9	10	19	14.8
Engineers	13	14	27	21.1
Facility managers	13	7	20	15.6
Project managers	17	5	22	17.2
Owners	5	14	19	14.8
Tenants	9	12	21	16.5
Total	**66**	**62**	**128**	**100**

The survey provided five age groups to be chosen by respondents. Table 7.3 shows most respondents were in the age group 26 to 35 years old (51 or 39.8%) or the age group 46 to 55 (38 or 29.7%). Very few respondents (6 or 4.7%) were over 55 years old. A similar age distribution can be found in each role group.

Table 7.3. Characteristics of respondents (128 responses)

	Number of respondents						**Sub-total**	**% of total**
	Architects	**Engineers**	**Facility managers**	**Project managers**	**Owners**	**Tenants**		
Age								
≤ 25	3	3	2	2	3	4	17	13.3
26–35	9	10	9	12	5	6	51	39.8
36–45	4	1	2	4	3	2	16	12.5
46–55	3	12	6	2	6	9	38	29.7
≥ 56	0	1	1	2	2	0	6	4.7
Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Region								
North	9	15	9	13	14	12	72	56.2
South	10	12	11	9	5	9	56	43.8
Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**

Table 7.3 also shows the regions respondents were from. Over half (56.2%) of respondents were from northern China, and the rest (43.8%) were from southern China. By different roles, 14 of the 19 owners were from the north, and only 5 were from the south, but in other role groups, the location distribution was approximately even.

To understand respondents' experience with building retrofitting, three questions were asked: how long they have been working in the field of property management, how often they conduct retrofitting projects, and how many retrofitting projects they have conducted in the past three years. Table 7.4 shows that 53.9% of the respondents have worked in the field for 5 years or less, 15.6% have worked in the field for 6 to 10 years, and the rest (30.5%) of them have worked in the field for over 10 years. It can be stated that respondents of the survey can represent the group of professionals with working experience in the property management industry.

Table 7.4. Related experience of respondents (128 responses)

	Number of respondents						**Sub-total**	**% of total**
	Architects	**Engineers**	**Facility managers**	**Project managers**	**Owners**	**Tenants**		
Working years in the field of property management								
≤ 5	11	9	12	10	11	16	69	53.9
6–10	2	7	2	6	2	1	20	15.6
11–15	2	3	3	2	0	0	10	7.8
16–20	3	4	3	1	2	0	13	10.2
≥ 21	1	4	0	3	4	4	16	12.5
Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Frequency of conducting retrofitting projects								
Always	1	1	1	0	1	0	4	3.1
Very often	1	3	4	3	0	1	12	9.4
Sometimes	11	11	7	13	7	5	54	42.2
Rarely	4	7	6	4	8	9	38	29.7
Never	2	5	2	2	3	6	20	15.6
Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Numbers of retrofitting projects conducted in the past 3 years								
0	2	7	5	5	7	8	34	26.6
1–3	10	18	11	14	11	12	76	59.4
4–7	5	2	1	2	0	0	10	7.8
8–11	1	0	3	0	0	0	4	3
12–14	1	0	0	0	0	1	2	1.6
≥ 15	0	0	0	1	1	0	2	1.6
Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**

Based on Table 7.4, most respondents were sometimes (42.2%) or rarely (29.7%) involved in a retrofitting project. In the past three years, 59.4% of respondents had conducted 1 to 3 retrofitting projects, and 26.6% had not undertaken a retrofitting project. Only 14% of respondents were involved in more than three retrofitting projects in the past three years. The low frequency of conducting retrofitting projects reflected that, in China, retrofitting has not been commonly considered a solution for improving the sustainable performance of existing buildings. New construction is still attracting more attention than existing buildings in China. Based on Huo et al. (2019) and Liu et al. (2019), from 2000 to 2015, about 28.4 billion m^2 of new construction was added in China, and China is still witnessing a dramatic increase in new construction. Therefore, it is urgent to improve the performance of existing buildings in China to maintain an average of sound performance for the whole building sector.

The type of buildings the respondents had ever retrofitted included residential buildings, office buildings, industrial buildings, shopping malls, school buildings and hospitals, as Table 7.5 shows. Residential buildings were the most common type of building being retrofitted (63.3%), followed by office buildings (34.4%). Hospital buildings were seldom retrofitted by respondents (3.1%). A similar situation can be found in each role group.

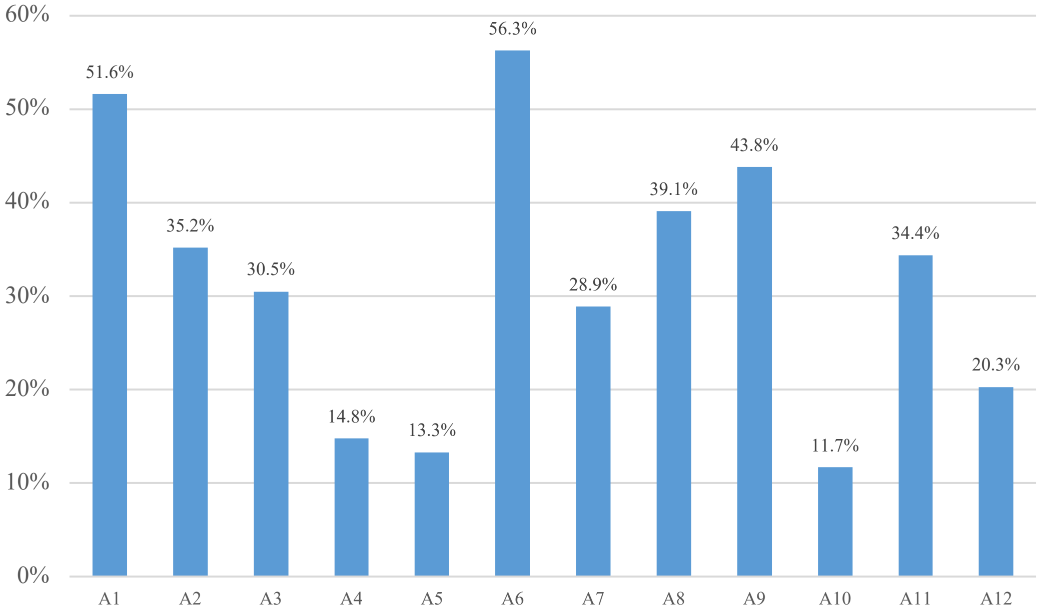
Table 7.5. Type of buildings ever retrofitted by respondents (128 responses, more than one choice possible)

Building type	**% of the role group**						**% of total**
	Architects	**Engineers**	**Facility managers**	**Project managers**	**Owners**	**Tenants**	
Residential	68.4	51.9	70	72.7	63.2	57.1	63.3
Office	31.6	33.3	25	54.5	31.6	18.6	34.4
Industry	21.1	14.8	5	18.2	0	9.5	11.7
Shopping mall	21.1	11.1	20	22.7	5.3	9.5	14.8
School building	15.8	18.5	0	9.1	21.1	14.3	13.3
Hospital	0	7.4	0	9.1	0	0	3.1

b) Development of sustainable retrofitting in China

Four questions were asked to understand the development of sustainable retrofitting in China. First, respondents were asked to choose retrofitting activities that they had ever used from provided options. More than one retrofitting activity could be chosen. Apart from the provided options, if there were others they had ever used, they could also add them at “others”. The frequency of chosen retrofitting activities is illustrated in Figure 7.1. The three most undertaken retrofitting activities were A6 – Upgrade lifts to more energy efficient ones (56.3%), A1 – Install/upgrade insulation of building envelopes (51.6%) and A9 – Install PV panel (43.8%). The three least common activities were A4 – Install sun shading devices (14.8%), A5 – Install BMCS (13.3%) and A10 – Install water control sensors (11.7%).

Figure 7.1. Frequency of commonly undertaken retrofitting activities by respondents (128 respondents, more than one activity possible)



A1. Install/upgrade insulation of building envelopes
A2. Adopt extensive green roof
A3. Change windows to energy efficient windows
A4. Install sun shading devices
A5. Install BMCS
A6. Upgrade lifts to more energy efficient ones
A7. Upgrade HVAC system
A8. Upgrade lighting system
A9. Install PV panel
A10. Install water control sensors
A11. Replace existing water fixtures with water efficient ones
A12. Install a water treatment system

As discussed in the beginning of Section 7.3.1.3, the geographical features, natural conditions and people's living behaviour in northern and southern China are different. Therefore, the Chi-square test was used to test whether regions affect the choice of common retrofitting activities, with a 95% confidence level. If the p-value (asymptotic significance) is less than 0.05, the region of respondents is associated with the type of retrofitting activities; otherwise, they are not associated. The results are summarised in Table 7.6, and the SPSS results are in Appendix B-4. Five of the total activities are associated with the region of respondents: A1 – Install/upgrade insulation of building envelopes, A4 – Install sun shading devices, A7 – Upgrade HVAC system, A8 – Upgrade lighting system, and A12 – Install water treatment system.

Table 7.6. Chi-Square test between commonly used retrofitting activities and region (128 responses)

Retrofitting activities	Chi-Square test		Result
A1. Install/upgrade insulation of building envelopes	$p<0.05$	$\chi(1) = 10.012$, p=0.002	**Associated**
A2. Adopt extensive green roof	$p>0.05$	$\chi(2) = 1.329$, p=0.514	Not associated
A3. Change windows to energy efficient windows	$p>0.05$	$\chi(1) = 1.405$, p=0.236	Not associated
A4. Install sun shading devices	$p<0.05$	$\chi(1) = 11.232$, p=0.001	**Associated**
A5. Install BMCS	$p>0.05$	$\chi(1) = 1.810$, p=0.179	Not associated
A6. Upgrade lifts to more energy efficient ones	$p>0.05$	$\chi(1) = 1.580$, p=0.209	Not associated
A7. Upgrade HVAC system	$p<0.05$	$\chi(1) = 11.997$, p=0.001	**Associated**
A8. Upgrade lighting system to improve energy efficiency	$p<0.05$	$\chi(1) = 5.003$, p=0.025	**Associated**
A9. Install PV panel	$p>0.05$	$\chi(1) = 2.612$, p=0.106	Not associated
A10. Install water control system	$p>0.05$	$\chi(1) = 0.059$, p=0.859	Not associated
A11. Replace existing water fixtures with more water efficient ones	$p>0.05$	$\chi(1) = 0.431$, p=0.512	Not associated
A12. Install a water retreatment system	$P<0.05$	$\chi(1) = 4.195$, p=0.041	**Associated**

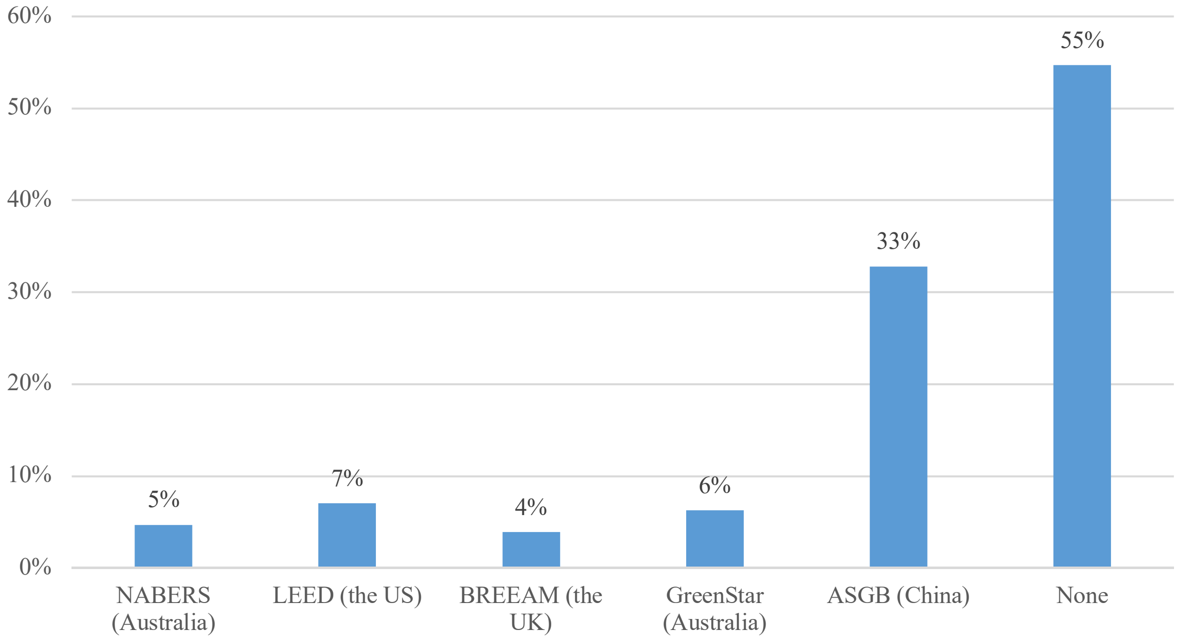
As discussed in Section 7.4.1.3, northern China has a district heating supply for its cold and dry winter, and this supply is not provided in the southern region. Therefore, HVAC is important for people living in the south to adjust the indoor temperature, while the insulation performance of building envelopes is important for buildings in the north to reduce heat loss in winter and gain in summer. Therefore, more respondents from northern China have undertaken the retrofitting activity of upgrading the insulation of building envelopes.

The survey showed that about 50% of respondents from the south have ever undertaken the retrofitting activity A8 – Upgrade lighting system, but only 31% of those from the north have used it. With sufficient natural light in southern China, sun shading devices are essential if no window film adheres to glazing. Therefore only 6% of northern respondents had undertaken activity A4 – Add sun shading devices, which is much lower than the southern respondents. Due to the greater precipitation in southern China, the retrofitting activity A12– Install water treatment system was more likely to have been undertaken by respondents from southern China than those from northern China.

Based on the above discussion, each of the retrofitting activities offered had been used at one time or another by some respondents. However, due to location variations, some of them were more likely to be used in the north, such as improving insulation of building envelopes; and some of them were more likely to be used in the south, such as upgrading HVAC, upgrading the lighting system, installing sun shading devices, and installing a water treatment system. The operating model is intended to be suitable for use across China. Therefore, all these retrofitting activities should be included, and suitable ones can be selected when using the operating model to develop retrofitting strategies for the case building.

To understand what sustainability assessment tools are commonly used in China, the survey provided options for respondents, including popular tools used both widely in China (ASGB) and across the world (Green Star and NABERS in Australia, LEED in the US, and BREEAM in the UK). The frequency of selections by respondents is illustrated in Figure 7.2. It shows that 33% of respondents have used ASGB to assess the sustainable performance of existing buildings, mainly because it works as a design guide established by the Chinese government. However, the focus of the ASGB assessment tool is on new buildings instead of existing buildings. Moreover, it is a self-assessment system, in which assessment results may be less accurate and reliable.

Figure 7.2. Frequency of using sustainable assessment tools (128 respondents, more than one choice possible)



Other assessment tools were seldom used by respondents as less than 10% of respondents had ever used any of them. Moreover, over half of respondents (55%) indicated that they have never used any assessment tools to assess the performance of existing buildings. It can be considered that using assessment tools is not a major measure to improve the sustainability performance of existing buildings in China.

For the question on who should be responsible for improving sustainability, four options were provided in the survey, and more than one option could be chosen. The result in Table 7.7 shows that respondents believed the government should mainly be responsible for improving sustainability. In total, 68.8% of respondents believed that government should take responsibility by establishing relevant regulations. 65.6% thought that government and industry should improve sustainability jointly, and 58.6% thought that government should take responsibility by using financial incentives. In contrast, only 25.8% of respondents said individual owners and facility managers should take responsibility.

Table 7.7. The parties who should take responsibility for improving sustainability (128 respondents, more than one choice possible)

Responsibility	**% in each role group**						**% of total**
	Architects	**Engineers**	**Facility managers**	**Project managers**	**Owners**	**Tenants**	
Government through regulation	73.7	63	90	63.6	63.2	61.9	68.8
Government through financial incentives	47.4	59.3	55	68.2	47.4	71.4	58.6
Government and industry jointly	78.9	78.9	75	59.1	63.2	66.7	65.6
Individual owners and managers	36.8	42.1	25	27.3	21.1	14.3	25.8

Based on Table 7.7, an interesting phenomenon is observed. In most role groups, the options of government through regulation, and government and industry jointly, received the most support for taking responsibility for improving sustainability. However, the option that government should take responsibility through financial incentives received the most support from project managers and tenants. Moreover, even though most role groups did not consider that individual owners and managers are responsible for improving sustainability, 42.1% of engineers still believed owners and managers should take responsibility for promoting sustainability. It indicates that the understanding and demands of sustainable buildings vary across stakeholders.

The last question in this part was about the drivers of sustainable retrofitting. Respondents could choose more than one from the provided options. The responses by different groups of roles are illustrated in Table 7.8. More than half of engineers (56%), facility managers (75%), project managers (59.1%), owners (52.6%) and tenants (66.7%) believed that tenants' requirements were the driver, while 75% of facility managers, 86.4% of project managers, 52.6% of architects, and 59.1% of project managers believed that market requests were the driver. Overall, the main drivers of sustainable retrofitting were believed to be tenants' requirements and market requests, indicating that sustainable retrofitting would be more desired and promoted if tenants and the professionals in the market could better understand the benefits of sustainable retrofitting.

Table 7.8. Drivers of sustainable retrofitting by role group (128 respondents, more than one choice possible)

Drive	**% in each role group**						**% of total**
	Architects	**Engineers**	**Facility managers**	**Project managers**	**Owners**	**Tenants**	
Tenants' requirement	36.8	55.6	75	59.1	52.6	66.7	57.5
Government	52.6	48.1	45	45.5	42.1	33.3	44.5
Economic payback	47.4	37	55	59.1	26.3	28.6	42.2
Images/Brand	36.8	37	30	36.4	21.1	33.3	32.8
Market request	52.6	48.1	75	86.4	47.4	42.9	58.6
Support and promotion from related organisations	26.3	22.2	15	4.5	5.3	23.8	16.4

c) Importance level of different aspects of sustainability

As discussed in Chapter 2, sustainable development is evaluated in a three-dimensional model of environmental, economic and social dimensions. To understand the importance of these dimensions, a five-point Likert scale was provided for respondents to express their judgment, where 1 is not important, 2 is slightly important, 3 is moderately important, 4 is important, and 5 is very important. The rating scores given by respondents are shown in Table 7.9.

Table 7.9. Importance ratings of different aspects of sustainability by role group (128 respondents)

Aspects of sustainability	**Level of importance**	**Number of respondents**						**Sub-total**	**% of total**
		Architects	**Engineers**	**Facility managers**	**Project managers**	**Owners**	**Tenants**		
Environmental	Not or Slightly	0	1	2	0	0	0	3	2.3
	Moderately	2	4	0	0	1	3	10	7.8
	Important or Very	17	22	18	22	18	18	115	89.9
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Economic	Not or Slightly	1	2	2	1	4	2	12	9.4
	Moderately	1	9	2	2	3	4	21	16.3
	Important or Very	17	16	16	19	12	15	95	74.3
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Social	Not or Slightly	1	6	2	0	2	1	12	9.4
	Moderately	7	9	6	8	3	3	36	28.1
	Important or Very	11	12	12	14	14	17	80	62.5
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**

About 90% of respondents agreed that environmental impact is important or very important as an aspect of sustainability, about 74.3% of respondents agreed that economic is an important or very important dimension of sustainability, and 62.5% of respondents agreed that social is important or very important. For each role group, a similar situation can be observed: most of them believed these aspects are important or very important. Among these three dimensions, social received the least support, consistent with the gap identified in the literature review that the social dimension does not get as much attention as the environmental and economic dimensions get.

To explore whether the given rating scores are affected by respondents' age, Table 7.10 illustrates the distribution of rating scores by age group. As Table 7.9 showed most respondents believed that the three sustainability dimensions are important or very important, Table 7.10 summarises results by age group.

Table 7.10. Importance rating scores on the three sustainability dimensions by age group (128 respondents)

Sustainability dimensions	Level of importance	Number of respondents in each age group					Total
		≤25	26–35	36–45	46–55	≥56	
Environmental	Not or Slightly	1	1	0	1	0	3
	Moderately	3	1	1	5	0	10
	Important or Very	13	49	15	32	6	115
	Total	**17**	**51**	**16**	**38**	**6**	**128**
Economic	Not or Slightly	1	3	0	7	1	12
	Moderately	3	4	3	9	2	21
	Important or Very	13	44	13	22	3	95
	Total	**17**	**51**	**16**	**38**	**6**	**128**
Social	Not or Slightly	1	5	1	3	2	12
	Moderately	6	13	4	12	1	36
	Important or Very	10	33	11	23	3	80
	Total	**17**	**51**	**16**	**38**	**6**	**128**

On the environmental dimension, 13 respondents believed it is not, slightly, or moderately important, with 6 of them (46.2%) in the age group 46 to 55 years old. Of the 33 respondents believing the economic dimension is not, slightly, or moderately important, about 57.6% of them are over 46 years old. On the social dimension, 48 respondents believed it is not, slightly, or moderately important, with about 37.5% of them over 46 years old, and another 37.5% in the age group 26 to 35 years old. In general, more responses for not, slightly, or moderately important of the three sustainability dimensions were from respondents of older ages, with younger people more interested in sustainability.

To test whether the identified assessment criteria under the environmental dimension are applicable in China, respondents were asked to give rating scores for them. As Table 7.11 shows, most of them believed they are important or very important.

Table 7.11. Importance ratings of different criteria under environmental dimension by role group (128 respondents)

Environmental variables	**Level of importance**	**Number of respondents**						**Sub-total**	**% of total**
		Architects	**Engineers**	**Facility managers**	**Project managers**	**Owners**	**Tenants**		
Reduce energy consumption	Not or Slightly	0	1	2	0	0	0	3	2.3
	Moderately	3	1	1	3	1	1	10	7.8
	Important or Very	16	25	17	19	18	20	115	89.9
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Reduce carbon emissions	Not or Slightly	0	2	0	1	0	0	3	2.4
	Moderately	1	2	3	2	3	1	12	9.4
	Important or Very	18	23	17	19	16	20	113	88.2
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Reduce water consumption	Not or Slightly	0	1	0	0	1	0	2	1.6
	Moderately	1	2	0	3	2	3	11	8.6
	Important or Very	18	14	20	19	16	18	115	89.8
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Use reusable or recyclable materials or components	Not or Slightly	1	2	0	1	0	2	6	4.7
	Moderately	6	6	4	6	6	5	33	25.7
	Important or Very	12	19	16	15	13	14	89	69.6
	Total	**19**	**27**	**20**	**22**	**21**	**21**	**128**	**100**
Reduce waste generation	Not or Slightly	0	2	1	1	0	2	6	4.7
	Moderately	3	4	2	5	0	2	16	12.5
	Important or Very	16	21	17	16	19	17	106	82.8
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Improve indoor environmental quality	Not or Slightly	0	0	1	0	0	0	1	0.8
	Moderately	1	1	1	2	2	4	11	8.6
	Important or Very	18	26	18	20	17	17	116	90.6
	Total	**19**	**27**	**19**	**22**	**19**	**21**	**128**	**100**

As Table 7.10 shows that there are about 34.4% of all the respondents who have ever worked on projects involving office buildings. Since these identified assessment criteria are for office buildings, it is necessary to test whether the choice of importance level of these environmental assessment criteria are impacted by whether the respondents have experience of working on office buildings. The Chi-square test with a 95% confidence level was conducted to check whether the association exists. If the *p*-value (asymptotic significance) is less than 0.05, the experience of working on office buildings is associated with the decision on importance level of environmental assessment criteria; otherwise, they are not associated. The SPSS results are in Appendix B-5, and the results indicate that all the *p*-value are bigger than 0.05, which means that the decided importance level of the environmental assessment criteria is not associated with respondents' experience of working on office buildings.

Similarly, respondents also gave rating scores for identified social assessment criteria. The same as the environmental dimension, respondents in different role groups held the same opinion. Most believed that all the identified assessment criteria are important or very important, as Table 7.13 shows. Except for the listed assessment criteria, one social assessment criterion was also mentioned, impact on surrounding traffic and pedestrians. Whether the criteria are applicable, and how important they are, is discussed in the focus group discussion in Section 7.4.2.

Table 7.13. Importance ratings of different criteria under social dimension by role group (128 respondents)

Social variables	**Level of importance**	**Number of respondents**						**Sub-total**	**% of total**
		Architects	**Engineers**	**Facility managers**	**Project managers**	**Owners**	**Tenants**		
Noise impact on neighbourhood	Not or Slightly	0	0	0	0	0	0	0	0
	Moderately	5	4	2	3	1	2	17	13.3
	Important or Very	14	23	18	19	18	19	111	86.7
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Emission impact on neighbourhood	Not or Slightly	0	0	0	0	0	0	0	0
	Moderately	2	4	2	3	2	2	15	11.7
	Important or Very	17	23	18	19	17	19	113	88.3
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Impact from glare or overshadowing neighbourhood	Not or Slightly	0	0	0	0	0	0	0	0
	Moderately	3	2	2	2	1	3	13	10.2
	Important or Very	16	25	18	20	18	18	115	89.8
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Safety and security	Not or Slightly	1	1	0	0	0	0	2	1.6
	Moderately	2	1	1	2	0	0	6	4.7
	Important or Very	16	25	19	20	19	21	120	93.7
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Impact on cultural heritage	Not or Slightly	0	1	0	0	0	1	2	1.6
	Moderately	2	3	4	2	1	2	14	10.9
	Important or Very	17	23	16	20	18	18	112	87.5
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Accessibility to building facilities for people with special needs	Not or Slightly	0	3	0	1	0	0	4	3.2
	Moderately	3	3	0	3	2	4	15	11.7
	Important or Very	16	21	20	18	17	17	109	85.1
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Accessibility to building services	Not or Slightly	0	2	0	1	0	1	4	3.1
	Moderately	3	6	2	1	4	5	21	16.4
	Important or Very	16	19	18	20	15	15	103	80.5
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**
Impact on maintenance and maintainability from newly added building fabrics or building systems	Not or Slightly	0	1	0	0	0	0	1	0.8
	Moderately	3	3	3	6	3	4	22	17.1
	Important or Very	16	23	17	16	16	17	105	82.1
	Total	**19**	**27**	**20**	**22**	**19**	**21**	**128**	**100**

Same as the environmental assessment criteria, the Chi-square test with a 95% confidence level was also conducted here to check whether there is an association between the decided importance level of the social assessment criteria and the respondents' experience of working on office buildings. The SPSS results are in Appendix B-6, and the results show that all the *p*-value are bigger than 0.05, which means that the association does not exist.

In summary, the identified aspects of sustainable development and assessment criteria under environmental and social dimensions were generally believed to be important and should be included in this study. The other assessment criteria mentioned by respondents are included in focus group discussions to determine their necessity and importance.

d) Further discussion about improvement of sustainable retrofitting

Three open-ended questions in the last part of the survey further discussed the methods to improve the development of sustainable retrofitting, but they were not mandatory. Therefore, not all the respondents answered these questions, but some valuable responses are discussed.

The first question was for owners or tenants of office buildings who were asked about what improvement they expect from sustainable retrofitting. Two of the owners expressed that they expected improvement in several aspects of the building, including comfort level, the beauty of the interior and exterior of the building, and safety level, but the most important is that the cost of retrofitting is low. They explained that cost could be reduced by using materials and labour at a low price and in other ways like reusing recycled materials and components. The other owner expressed that the most expected improvement by retrofitting is upgraded building facilities by replacing aging facilities and systems such as pipes and circuit systems.

For tenants, a safe and healthy working environment was the most expected improvement. Even though responses were limited, the different demands of owners and tenants for retrofitting can still be summarised that both owners and tenants expect improvement of buildings' performance from retrofitting. Owners would like improved performance with lower cost, and most tenants do not care about cost much.

The same question was asked to professionals who provided their opinions based on their professional experience. They expected five aspects to be improved by sustainable retrofitting:

(1) All professionals believed sustainable retrofitting could be realised by appropriate

planning and wise determination of a retrofitting strategy, which can ensure building space is used more reasonably and effectively and meets different tenants' needs.

(2) Selection of building materials is essential for achieving high quality of retrofitting. Materials with good quality should be encouraged to reduce the frequency of replacement. The use of reusable and recyclable materials can also help alleviate adverse impacts on the environment and ecology.

(3) Architects, engineers and facility managers emphasised that different stages of existing buildings should be considered for determining retrofitting strategies. In other words, the long-term perspective should be taken to achieve sustainable retrofitting.

(4) Project managers believed that advanced technology and equipment should be applied for retrofitting, such as smart control systems, so existing buildings can become "smarter" to manage and control.

(5) The public's awareness of sustainability should be improved. If people understand the benefits of sustainable retrofitting that can be obtained by different stakeholders, at different stages, and in various forms, more people would support retrofitting existing buildings.

The last question was on what other actions, except for retrofitting, should be taken to improve the performance of existing buildings. Fifteen responses were received from six groups of respondents. Summarising these responses, two major actions are suggested: providing education for tenants and owners about how to properly use and manage existing buildings, and establishing relevant standards for regulating the retrofitting process. Since owners and tenants do not have sufficient knowledge about property management, most do not know how to use building facilities properly or do not pay attention to energy and resource-saving when they use the building. For example, if motion sensors are not installed in an office building, the lights would not be turned off automatically after people leave the office. In this case, if tenants were more aware of energy efficiency, they would manually turn off the lights so that energy is not wasted. Another example is that much energy can be saved if tenants understand to close windows and doors when the air conditioner is on. In addition, the relevant standards play a significant role in regulating the performance level of buildings. If the benchmarking is reasonable and regulation is strict, improvement by retrofitting can be largely achieved.

7.4.1.6. Outcomes of the survey

Based on the literature review and analysis of the questionnaire survey, all provided retrofitting activities are applicable for retrofitting office buildings in China (as shown in Figure 6.3 in Chapter 6). The assessment criteria under the three dimensions applicable in the context of sustainable retrofitting in China are listed in Table 7.13.

Table 7.13. Assessment criteria from questionnaire survey

Life stages	Environmental assessment criteria	Economic assessment criteria	Social assessment criteria
Retrofitting stage	• Energy consumption • Carbon emissions • Use of recyclable/reusable materials • Waste generation	• Initial cost	• Noise impacts on neighbourhood • Emission impacts on neighbourhood • Safety of retrofitting construction • Impact on cultural heritage • Impact on surrounding traffic and pedestrians*
Operation stage	• Energy consumption • Carbon emissions • Use of recyclable/reusable materials • Waste generation • Indoor environmental quality • Water consumption	• Operation cost • Replacement cost • Maintenance cost	• Impacts from glare or overshadowing neighbourhood • Safety and security of users (e.g., security entrance, CCTV, etc.) • Accessibility to building facilities for people with special needs • Accessibility to building services • Impact on maintenance and maintainability from newly added building fabrics or building systems

Note. * the item is added via survey and is further determined by focus group discussions

7.4.2. Stage 2 – Focus groups

Since the information collected by the survey is broad, and the response rate and sample size cannot be calculated when using snowball sampling, it was necessary to conduct another data collection method to consolidate and explain the survey results. As discussed at the beginning of Section 7.4, focus group discussion is a suitable method, which can consolidate the survey results, and also modify the assessment criteria further to be suitable for adapting the conceptual model to use for the case building and other buildings in China. The focus group discussion is a good chance to understand the interplay of different aspects of sustainability among various stakeholders. As well as to modify the conceptual model, the focus group discussions are also conducted to estimate weights for the three sustainability dimensions and assessment criteria.

7.4.2.1. Participants in the focus group discussions

To consolidate the results of the survey and further specify the model to suit the local situation of the case building, the same role groups as the questionnaire survey were invited for focus group discussions. One of the researcher's supervisors has connections with local professionals and key stakeholders of retrofitting in China. Twenty invitations were sent, and 14 replies were received expressing interest in participating in the focus group discussion. Since no replies from owners of office buildings were received, no building owners participated in the focus group discussion. Due to time clashes, three focus group discussions were organised at different places and times for participants' convenience. Each focus group discussion was held for one to two hours, depending on the number of participants. The participants in each focus group are summarised in Table 7.14.

Table 7.14. Categories of participants in the focus group discussion

Category	Role	Number of participants
Professionals from academia	Architect	3
	Engineer	2
	Facility manager	1
	Project manager	1
Professionals from industry	Architect	1
	Engineer	2
	Project manager	1
Others	Owner	0
	Tenant	3
Total		14

7.4.2.2. Focus group discussion

The details of the three focus group discussions are listed in Table 7.15. The participant information sheet and consent form were sent to each participant prior to the discussion (see Appendix C-1 and C-2). It took about 15 minutes for them to read, sign and return the completed consent form before the commence of the discussion. Four main questions were asked to help participants express their opinions and guide discussions within the scope of the study.

Table 7.15. Details about focus group discussions

	Date	Location	Period	Moderator	Notetaker	Participants
1	7 May 2019	Zhejiang University City College	2 hours	External supervisor	Researcher	7 professionals from academia
2	10 May 2019	An architectural design company in Hangzhou	1.5 hours	Researcher	Researcher	4 professionals from the industry
3	15 May 2019	A cafe in Hangzhou	1 hour	Researcher	Researcher	3 office building tenants

- Question 1: What is your understanding of the environmental, economic and social dimensions of sustainability?
- Question 2: What are the challenges of retrofitting?
- Question 3: What retrofitting activities are commonly applied in Hangzhou?
- Question 4: Are the identified environmental and social assessment criteria relevant to retrofitting projects in Hangzhou, and how important are they?

7.4.2.3. Analysis of focus group discussion

The discussion is categorised into four parts. First, issues concerned with the three sustainability pillars are discussed. Then, obstacles faced by local sustainable retrofitting mentioned throughout the discussion are also summarised in Table 7.16. Based on the understanding of local sustainable retrofitting, participants were asked to give rating scores on the provided retrofitting activities and assessment criteria to justify whether they are suitable for the case study in Hangzhou. If there was something that they believe should be added, modified or deleted, they needed to give a reason for these changes.

Table 7.16. Summary of focus group discussions

Discussion		Professionals from academia	Professionals from industry	Tenants
Concerns on three pillars	Environmental issues	• Indoor environmental quality • Waste management • Carbon emissions are not emphasised in China • Acoustic comfort is always neglected • Impacts from retrofitting construction are always neglected • Poor thermal performance is the main reason for retrofitting • This dimension is only considered for meeting relevant regulations	• This dimension is not emphasised at the stage of planning and construction • Energy consumption is only considered for achieving a green building label • The environmental impact will be considered if the retrofitting activities can bring financial benefits • Owners do not think this dimension is important	• Indoor visual comfort • Indoor air quality • Greenery level • The most expected improvement by retrofitting is the performance of HVAC • Structure defect is the main reason for retrofitting • This dimension is not the primary consideration of tenants
	Economic issues	• The initial cost is the primary concern of owners • The payback period is important for assessing the economic performance of retrofitting • LCC should be employed to assess the economic performance of retrofitting from a long-term perspective • Split benefit between owners and tenants is an obstacle to retrofitting	• The budget of retrofitting determines the scale and quality of retrofitting and frequency of retrofitting • Owners consider initial costs more important than other costs	• Tenants also pay for retrofitting as retrofitting is regarded as part of maintenance
	Social issues	• Inappropriate use by tenants • Retrofitting frequency • Lack of consideration for people with additional needs • Impact on culture	• Retrofitting frequency	• Accessibility to building facility and building service • Indoor environment for good wellbeing and higher work efficiency • Tenants' use behaviour
Obstacles		• Voices from tenants are hardly heard • A limited database about energy consumption is available in China • Different work formats for retrofitting from western countries	• Information about retrofitting construction is limited in China • Lack of mature assessment standards for retrofitting in China • Limited support from the government, especially financial support	• Tenants' opinions should be considered for retrofitting

For environmental issues, indoor environmental quality, including indoor thermal comfort, air quality, acoustic comfort and visual comfort, is the primary concern. However, acoustic performance is always neglected at the early stage of planning and construction. Professionals from academia also mentioned that waste management is essential to environmental sustainability. They also stated that energy consumption and carbon emissions are rarely a concern for retrofitting in China unless for meeting relevant regulations or achieving a green building label. Moreover, the focus on reducing negative impacts on the environment is mainly at the operation stage. Impacts from retrofitting construction are seldom considered. In summary, improving indoor environmental quality is believed to be the main content under the environmental dimension. Reducing negative impacts on the environment is only considered under the have-to situation, which is normally not considered by building owners and tenants.

For the economic dimension, the importance of initial cost is emphasised, especially for owners who pay for retrofitting. Whether the initial cost of retrofitting is acceptable determines the scale and quality of the retrofitting. Another reason for owners avoiding retrofitting is the split benefit. Tenants receive the benefits of high initial costs instead of the owners who pay for it. The split benefit between owners and tenants is regarded as a significant obstacle for retrofitting.

Compared to the environmental and economic dimensions, the social dimension receives less attention. Some existing social issues were discussed, including lack of knowledge about sustainability leading to inappropriate use behaviour of tenants, and lack of consideration for people with additional needs such as the elderly, people with disability, and pregnant people. Tenants' wellbeing and work efficiency impacted by the indoor environment should also be considered. The impact of the frequency of retrofitting should also be included under the social dimension. Determining a proper time and frequency of retrofitting is important for reducing interruption to tenants.

In addition to issues in the three sustainability dimensions, participants also discussed obstacles faced by local sustainable retrofitting. First, they stated that tenants' requirements are the main driver of promoting sustainable retrofitting. However, through the process of determining retrofitting strategies, tenants are rarely involved. A new mechanism of deciding retrofitting strategies that allows tenants' voices to be heard is required. Second, in China, retrofitting is conducted mainly to improve thermal comfort. It is rare in China to consider all the environmental, economic and social dimensions for retrofitting. Besides, a mature assessment standard for sustainable retrofitting in China does not exist yet. China is still at the early stage of developing sustainable retrofitting.

Based on the above discussion, respondents were asked to modify the retrofitting activities and assessment criteria to be suitable for local retrofitting projects. First, tables containing retrofitting activities and assessment criteria based on the survey results were sent out. If respondents believed something needed to be modified, added or deleted, they needed to explain why these changes were required. The related discussion is summarised in Table 7.17.

Table 7.17. Modification of retrofitting activities and assessment criteria

Discussion	**Professionals from academia**	**Professionals from industry**	**Tenants**
Retrofitting activities	• Adding or upgrading acoustic insulation for the walls that subdivide the tenancy areas	• No other changes are needed	• No other changes are needed
Assessment criteria	• The problem of glare or overshadowing neighbourhood is rarely considered when conducting retrofitting projects • The adaptability for different users should be considered	• Improved adaptability by retrofitting is desired since other tenants may require a different function	• Concern about relocating tenants during retrofitting

In the three focus group discussions, professionals from academia proposed one new retrofitting activity of adding or upgrading acoustic insulation for the walls that subdivide the tenancy areas. They believed that it is a crucial activity for retrofitting office buildings, which can improve indoor acoustic comfort and offer more private space for tenants.

On assessment criteria, professionals suggested removing the assessment criterion of impact from glare and overshadowing the neighbourhood from the social dimension. They explained that the problem could not easily be solved by retrofitting and they could not recall any related practice based on their professional experience.

Two assessment criteria are added for the social dimension. The first one is room flexibility. Based on the newly added retrofitting activity mentioned above, professionals from both academia and industry believed that the improvement of room flexibility needs to be added to the operation stage of the social dimension. If the adaptability of the building can be improved by retrofitting, different types of tenants can be attracted, such as office space catering for both architectural firms and IT companies. This makes the office building easy to rent out and may attract higher rents. The second criterion is added to the retrofitting stage in the social dimension by tenants – impacts on relocating current tenants. Tenants stated that whether tenants could be relocated during retrofitting can sometimes determine if retrofitting is acceptable or not.

Once no more changes were proposed, participants were asked to assign rating scores to determine the effectiveness of retrofitting activities and the importance of assessment criteria for applying them to local retrofitting projects. A 10-point scale was adopted, where a score of 1 represents the least effective or important, while a score of 10 represents the most effective or important. The average rating scores for retrofitting activities and assessment criteria are shown in Tables 7.18 and 7.19, respectively.

Table 7.18. Rating score on the effectiveness of retrofitting activities

Retrofitting activities	**Average rating score (max 10)**
A1. Install/upgrade insulation of building envelopes	9.09
A2. Adopt extensive green roof	7.64
A3. Replace existing windows (glazing and/or frames) with energy efficient ones	8
A4. Install sun shading devices	7.45
A5. Install building management control system (BMCS)	7
A6. Upgrade lifts to more energy efficient ones	7.23
A7. Replace components or the whole HVAC system with a more efficient one	8.18
A8. Upgrade lighting system (including install motor sensors for lighting system, replace bulbs with T8, T5 or LED, and/or install daylight dimming control system)	7.90
A9. Install PV panels	8
A10. Install water control sensors	7.85
A11. Apply water-saving appliances and equipment (taps, toilet flushing equipment)	7.73
A12. Install water treatment system and reuse recycled water (storm, black and greywater)	7.55
A13. Add or upgrade acoustic insulation for the walls subdividing tenancy areas	7.91

Table 7.19. Rating score on importance of assessment criteria

		Assessment criteria	**Average rating score (max 10)**
Environmental dimension	Retrofitting stage	Energy consumption	8.21
		Carbon emissions	7.5
		Use of recyclable/reusable materials	7.36
		Waste generation	8.64
	Operation stage	Energy consumption	8.29
		Carbon emissions	7.79
		Use of recyclable/reusable materials	8.29
		Waste generation	7.86
		Indoor environmental quality	9.36
		Water consumption	8.14
Social dimension	Retrofitting stage	Noise impact on neighbourhood	8
		Emission impact on neighbourhood	8
		Safety of retrofitting construction	8.93
		Impact on cultural heritage	7.64
		Impact on surrounding traffic and pedestrians	7.79
		Impact on relocating tenants	7.93
	Operation stage	Accessibility to building facilities for people with special needs	8.43
		Accessibility to building services	8.71
		Impact on maintenance and maintainability from newly added building fabrics and building systems	8.43
		Safety and security of users	8.71
		Room flexibility for different demands	8.14

Based on Tables 7.18 and 7.19, the lowest rating score assigned to a retrofitting activity is 7, and the lowest score assigned to an assessment criteria is 7.36. It can be concluded that all provided retrofitting activities and assessment criteria are suitable to apply to local retrofitting projects. According to the specific situation of the case study, the necessary retrofitting activities and assessment criteria can be selected from Tables 7.18 and 7.19, respectively.

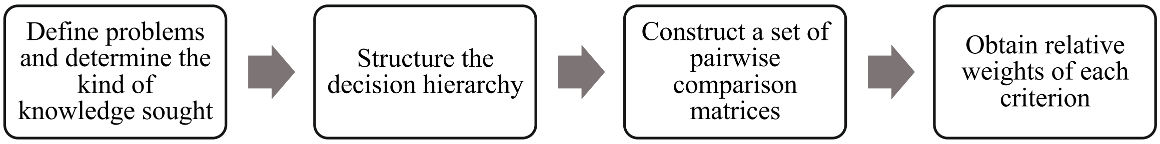
7.4.2.4. Outcomes of focus group discussions

Based on the focus group discussions, retrofitting activities and assessment criteria suitable for local retrofitting projects are finalised in Tables 7.18 and 7.19. The operating model for the case study has now been converted from the conceptual model. It can be used to develop retrofitting strategies for the case building based on steps illustrated in Chapter 6. At the end of the focus group discussions, participants were given a survey questionnaire to determine the weights of the three sustainability dimensions and assessment criteria under them using the AHP method. The details for determining weights are described in the following section.

7.5. Estimate weights by AHP method

According to the conceptual model developed in Chapter 6, the AHP method is adopted to determine weights. Figure 7.3 shows the steps to determine the level of importance or priority of assessment criteria using the AHP method (Saaty 2008).

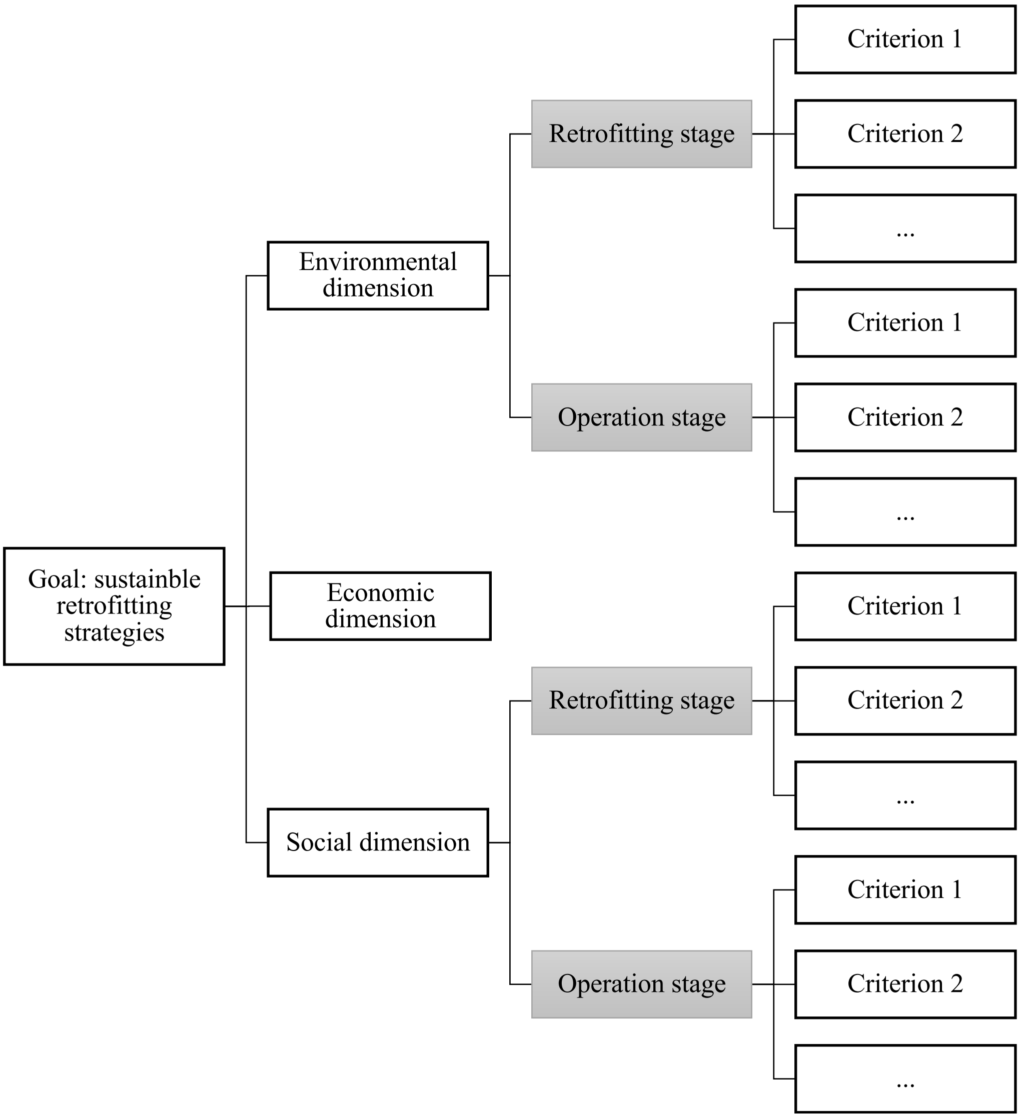
Figure 7.3. The flow of AHP method



Source: Saaty 2008

The developed assessment criteria should be structured in a hierarchical form. According to the discussion in Chapter 6, two levels of importance should be determined: the three sustainability pillars and the assessment criteria under them. These two levels are structured in a decision hierarchy as Figure 7.4 illustrates. Since both retrofitting and operation stages are considered, assessment criteria are categorised into these two stages correspondingly. The pairwise comparison, therefore, is done for each stage separately. In Figure 7.4, assessment criteria under the economic dimension are not shown because their level of importance is regarded as equal in the LCC method (see Section 6.7.2 in Chapter 6).

Figure 7.4. The hierarchy structure of assessment criteria



After structuring the decision in a hierarchy form, a fundamental scale, as Table 7.20 shows, is provided for participants of the focus group discussions to make the pairwise comparison.

Table 7.20. Fundamental scores for the AHP method

Intensity of Importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favour one over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favour one over another
6	Strong plus	
7	Very strong or demonstrated importance	A criterion is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one over another is of the highest possible order of affirmation
Reciprocals of above	If criterion i has one of the above non-zero numbers assigned to it when compared with criterion j, then j has the reciprocal value when compared with i	A reasonable assumption
1.1 – 1.9	If the criteria are very close	It may be challenging to assign the best value, but when compared with other contrasting criteria, the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the criteria.

Source: Saaty 2008

The last step in Figure 7.3 is to obtain relative weights, which is realised by collecting and calculating the geometric mean of individual judgment. The steps of this process are described in the following sections.

7.5.1. Design a questionnaire form to collect individual judgment

In this study, the participants of focus group discussions were also invited to complete a questionnaire form, designed to collect individual judgment on the level of importance between assessment criteria and the three sustainability dimensions. Assessment criteria under different life stages are structured in a pairwise form, as Table 7.21 shows. Each participant in the focus group discussion needed to fill in the table using the value score provided in Table 7.20. Due to the reciprocal relation between a pair of assessment criteria compared, only the triangle in the upper right hand in Table 7.21 needs to be defined. The lower left-hand triangle can be calculated based on the reciprocal relation, $c_{ij} = {}^{1}/_{c_{ji}}$.

Table 7.21. Pairwise comparison matrix for individual judgment

C_{ij}	Assessment criterion C_1	Assessment criterion C_2	⋯	Assessment criterion C_n
Assessment criterion C_1	c_{11}	c_{12}	⋯	c_{1n}
Assessment criterion C_2	c_{21}	c_{22}	⋯	c_{2n}
⋮	⋮	⋮	⋮	⋮
Assessment criterion C_n	c_{n1}	c_{n2}	⋯	c_{nn}

The form for collecting individual judgment is in Appendix D-1. With the collected individual judgments, the matrix of individual judgments can be constructed as Equation 7.1.

$$\mathrm{C} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{bmatrix} \qquad \text{Equation 7.1.}$$

For example, Table 7.17 shows that there are four assessment criteria in the retrofitting stage of the environmental dimension, and the matrix of the individual judgments can be constructed as Equation 7.2.

$$\mathrm{C} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \end{bmatrix} \qquad \text{Equation 7.2.}$$

7.5.2. Combine individual judgment matrix to reach group decision

The geographic mean is used to combine individual judgments into a group decision. Assuming there are k participants who compare the level of importance of n assessment criteria. With collected individual judgment in the last step, the group judgment matrix can be built, as Equation 7.3 shows.

$$C = \begin{bmatrix} \sqrt[k]{c_{11}^1 \times c_{11}^2 \times \cdots \times c_{11}^k} & \sqrt[k]{c_{12}^1 \times c_{12}^2 \times \cdots \times c_{12}^k} & \cdots & \sqrt[k]{c_{1n}^1 \times c_{1n}^2 \times \cdots \times c_{1n}^k} \\ \sqrt[k]{c_{21}^1 \times c_{21}^2 \times \cdots \times c_{21}^k} & \sqrt[k]{c_{22}^1 \times c_{22}^2 \times \cdots \times c_{22}^k} & \cdots & \sqrt[k]{c_{2n}^1 \times c_{2n}^2 \times \cdots \times c_{2n}^k} \\ \vdots & \vdots & \ddots & \vdots \\ \sqrt[k]{c_{n1}^1 \times c_{n1}^2 \times \cdots \times c_{n1}^k} & \sqrt[k]{c_{n2}^1 \times c_{n2}^2 \times \cdots \times c_{n2}^k} & \cdots & \sqrt[k]{c_{nn}^1 \times c_{nn}^2 \times \cdots \times c_{nn}^k} \end{bmatrix}$$

$$= \lambda_{max} W \qquad \text{Equation 7.3.}$$

Where,

C – the group judgment matrix
k – the number of participants who determine the weights
λ_{max} – the largest eigenvalue of a comparison matrix, which can be calculated using MATLAB
W – the corresponding eigenvector, the components in W are the weightings for each of the assessment criteria

Taking the assessment criteria in the retrofitting stage of the environmental dimension as an example, the matrix of group judgment can be illustrated in Table 7.22.

Table 7.22. Group judgment matrix on the environmental assessment criteria in the retrofitting stage

	Energy consumption	**Carbon emissions**	**Use of recyclable/reusable materials**	**Waste generation**
Energy consumption	1	1.013	0.964	1.021
Carbon emissions	0.987	1	0.967	0.9871
Use of recyclable/reusable materials	1.037	1.034	1	0.925
Waste generation	0.980	1.013	1.082	1

In this study, five matrices of group judgment were constructed for the level of importance of the environmental assessment criteria in the retrofitting stage, the environmental assessment criteria in the operation stage, the social assessment criteria in the retrofitting stage, the social assessment criteria in the operation stage, and the three sustainability dimensions. The details of establishing the matrix of group judgment for assessment criteria and the three sustainability dimensions are in Appendix D-2.

7.5.3. Consistency test

After the group judgment matrices are constructed, the consistency of the group judgment needs to be checked. The pairwise comparison may lead to inconsistent importance logic among all compared items. For example, A, B and C items are compared. In pairwise comparison, A is regarded as more important than B, B is more important than C, and C is more important than A. The importance loop among the three items is inconsistent, as the importance logic is A>B>C>A. In addition, inconsistency may arise from inappropriate relationships among compared items. For instance, A is twice as important as B, B is twice as important as C, and A is also regarded as twice as important as C in the pairwise comparison. However, based on the first two comparisons, A should be four times more important than C.

To avoid inconsistency, the consistency ratio is calculated based on Equations 7.4 and 7.5 to check the consistency of the group judgment matrix.

$$CR = \frac{CI}{RI} \qquad \text{Equation 7.4.}$$

$$CI = \frac{\lambda_{max}-n}{n-1} \qquad \text{Equation 7.5.}$$

Where,

CR – consistency ratio
CI – consistency index
RI – the random index, referring to Table 7.23
λ_{max} – the largest eigenvalue of a comparison matrix
n – the number of compared items in total

Table 7.23. Random index in AHP

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Note: n is the number of compared items
Source: Saaty 1990

Saaty (1990) stated that a judgment matrix can be regarded as consistent if the calculated CR is less than 0.1. Otherwise, the group judgment matrix needs to be rebuilt based on new individual judgment.

Before the participants of focus group discussions started the questionnaire form for pairwise comparison (referring to Section 7.4.1), the reciprocal relation between the objects of pairwise comparison and possible situations of inconsistency were explained to them. As a result, all the calculated consistency ratios (CR) of the constructed matrices of group judgment (see Section 7.4.2) are less than 0.1 (see Table 7.24). Therefore, these group judgments can be regarded as consistent.

Table 7.24. Consistency of the constructed matrices of group judgment

Matrix of group judgment		**No. of compared items**	λ_{max}	**RI**	**CI**	**CR**	**Consistent or not**
Assessment criteria in the environmental dimension	Retrofitting stage	4	4.002	0.9	0.001	0.001	Consistent
	Operation stage	6	6.078	1.24	0.016	0.013	Consistent
Assessment criteria in the social dimension	Retrofitting stage	6	6.017	1.24	0.003	0.002	Consistent
	Operation stage	5	5.007	1.12	0.002	0.002	Consistent
The three sustainability dimensions		3	3.001	0.58	0.0005	0.001	Consistent

Note: CI and CR are calculated based on Equations 7.4 and 7.5

7.5.4. Outcome of weights generation

After the valid group judgment matrix is formulated, the weights of compared items can be obtained by normalising the column and line weights of the matrix accordingly. In this way, the weights of each assessment can be attained. For the three sustainability dimensions, the weights can be obtained by repeating the above process but making the pairwise comparison only among these three dimensions. The detailed process of generating weights for assessment criteria and sustainability dimensions is in Appendices D-1 to D-3. The generated weights for assessment criteria and the three sustainability dimensions are summarised in Table 7.25 and Table 7.26.

Table 7.25. Weights of assessment criteria for the case study

		Assessment criteria	**Weights**
Environmental dimension	Retrofitting stage	Energy consumption	0.25
		Carbon emissions	0.245
		Use of recyclable/reusable materials	0.25
		Waste generation	0.255
		Total	**1**
	Operation stage	Energy consumption	0.219
		Carbon emissions	0.155
		Use of recyclable/reusable materials	0.155
		Waste generation	0.154
		Indoor environmental quality	0.189
		Water consumption	0.128
		Total	**1**
Social dimension	Retrofitting stage	Noise impact on neighbourhood	0.145
		Emission impact on neighbourhood	0.18
		Safety of retrofitting construction	0.227
		Impact on cultural heritage	0.148
		Impact on surrounding traffic and pedestrians	0.163
		Impact on relocating tenants	0.137
		Total	**1**
	Operation stage	Accessibility to building facilities for people with special needs	0.259
		Accessibility to building services	0.167
		Impact on maintenance and maintainability from newly added building fabrics and building systems	0.163
		Safety and security of users	0.222
		Room flexibility for different demands	0.189
		Total	**1**

Table 7.26. Weights of the three sustainability dimensions for the case study

Sustainability dimensions	**Weights**
Environmental	0.437
Economic	0.324
Social	0.239
Total	**1**

Based on the above discussion, the conceptual model has been converted to an operating model, which can be used to develop retrofitting strategies for office buildings in China. The next chapter illustrates the detailed process of using the operating model to develop retrofitting strategies for the case building.

7.6. Summary

This chapter illustrated how to convert the conceptual model to an operating model for dealing with locational variations. The conceptual model developed in Chapter 6 contained most information on deciding retrofitting strategies for office buildings. However, the retrofitting activities and assessment criteria in the conceptual model were identified based on the literature review. Before applying it to develop retrofitting strategies for an actual office building, they need to be adapted to suit the specific situation of the case building.

To verify the conceptual model, a case study was conducted in Hangzhou, China. Therefore, the conceptual model needed to be converted to an operating model based on the specific situation of the case building. First, a survey was conducted in China to investigate whether the identified retrofitting activities and assessment criteria are applicable for retrofitting projects in China. The current situation regarding sustainable retrofitting in China can also be understood through the survey. Then, three focus group discussions with local professionals and key stakeholders were conducted to consolidate the survey results and further modify the retrofitting activities and assessment criteria to be applicable for the case building and other office buildings in China. Based on the information collected from the survey and the focus group discussions, suitable retrofitting activities and assessment criteria were finalised. In this way, the operating model for retrofitting projects in China is established. In the focus group discussions, apart from asking participants' opinions about retrofitting activities and assessment criteria, participants were also invited to determine the weights of the three sustainability dimensions and finalised assessment criteria using the AHP method.

With the converted operating model and the determined weights of the three sustainability dimensions and assessment criteria under them, the second part of the case study is to use the operating model to develop retrofitting strategies for the case building, which is described in Chapter 8.

Chapter 8. Case study – Develop retrofitting strategies

8.1. Introduction

The last chapter converted the conceptual model to an operating model by modifying the retrofitting activities and assessment criteria to suit the specific situation of the local case building. In this chapter, the operating model is used to develop retrofitting strategies for the case building, according to the steps outlined in the conceptual model (Figure 6.2 in Chapter 6). Following the illustration of developing retrofitting strategies for the case building is an analysis discussing the outcomes of the case study and its limitations. Combining the process described in Chapters 7 and 8, the detailed process of using the conceptual model to develop retrofitting strategies for an office building is fully demonstrated, and it can be regarded as a logically and methodologically correct framework for the work done and to be done in the future.

8.2. Developing retrofitting strategies based on the operating model

The case building is an office building located in the centre of Hangzhou. Since its construction in 1985, it has never undergone a comprehensive evaluation of its performance or a well-planned retrofitting. Only some upgrades have been undertaken from time to time. Detailed information about the case building can be found in Section 7.3 of Chapter 7. The following sections illustrate how to use the operating model to develop retrofitting strategies for the case building.

8.2.1. Set retrofitting goals and identify problems of the case building

The preliminary demands of retrofitting from the main stakeholders are acquired by consulting the building owners, facility managers, and tenants. Building owners expressed that they tend to conduct sustainable retrofitting mainly to reduce current annual operation costs, and the target for reduction is 30% or more. Moreover, they would also like to obtain the national green building label, based on the Assessment Standard for Green Retrofitting of Existing Building (GB/T 51141-2015) (MOHURD 2015), as a way of advertising to attract higher rents. The building owners proposed a budget of CNY 3 million for the retrofitting project, which is about AUD 660,000 based on the currency rate in September 2022 (AUD 1 is equal to CNY 4.55). Speaking with the facility managers, they were concerned that the building was more than 35 years old and not equipped with a building management control system (BMCS), so the air conditioning and lighting can only be controlled manually. Therefore, they need to patrol after hours to ensure that the air conditioning and lights had been turned off. As for opinions from tenants, there is a suggestion box in the hall where tenants can put their opinions about the building and retrofitting. The major complaint was that they were unable to see images on computer monitors due to intensive sunlight at some times. Retrofitting was seen as an opportunity to solve this problem.

To further identify the building's problems, the finalised assessment criteria in the operating model (see Table 7.25 in Chapter 7) are used as a guideline for diagnosing problems of the case building. The records of electricity and water use in the past three years were also collected. Combining the issues raised by tenants and facility managers mentioned above, the problems are identified for the case building, as discussed below.

8.2.1.1. High energy consumption and carbon emissions

Electricity is the primary energy source for the case building. During the operation stage, electricity consumption and carbon emissions are mainly caused by operating different building service systems, such as HVAC and lighting. Based on the electricity bills in the past three years, the average annual electricity consumption is about 1,836,262 kWh or 93.29 kWh/m^2.

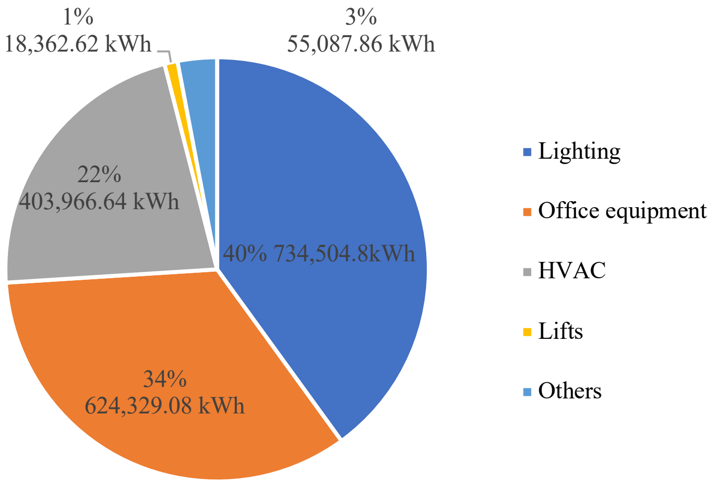
According to the study by Yu, Wu and Can (2020), there are 1,057 office buildings in Hangzhou, which can be categorised based on the "green" level and annual electricity consumption, as Table 8.1 shows. For conventional office buildings in Hangzhou, the average electricity consumption is about 64 kWh/m^2, and 51 kWh/m^2 for green buildings, resulting in a potential energy saving of 20% (Yu, Wu & Can 2020). Regarding this situation, the case building can be described as a conventional office building at electricity consumption level 2 as shown in Table 8.1 (93.29 kWh/m^2 per year). Compared with green office buildings with average electricity consumption of 51 kWh/m^2, it has an energy saving potential of about 45%.

Table 8.1. Categories of office buildings in Hangzhou

Office buildings	**Electricity consumption level 1 (less than 50 kWh/m^2)**	**Electricity consumption level 2 (between 50 and 100 kWh/m^2)**	**Electricity consumption level 3 (more than 100 kWh/m^2)**	**Total**
All office buildings (both conventional and green office buildings)	41%	47%	12%	100%
Conventional office buildings	35%	48%	17%	100%
Green office buildings	51%	39%	10%	100%

Source: Yu, Wu & Can 2020

Figure 8.1 shows the usage allocation of electricity by the case building based on the electricity bills in the past three years. Lighting, office equipment and the HVAC system are the three largest electricity consumers, with 40%, 34% and 22% of total yearly consumption, respectively. They should have the biggest potential for energy saving. However, retrofitting in this study does not involve upgrading office equipment. Therefore, performance improvement of the lighting system and HVAC system is the focus of the retrofitting project.



To identify the problems causing high energy consumption and carbon emissions, the retrofitting team audits the performance of building elements and service systems relating to electricity consumption. It is then compared with the benchmark by local regulations. The below problems are identified.

(1) Poor insulation of building envelopes

As discussed in Section 3.4.6 of Chapter 3, the insulation performance of building envelopes is highly related to the energy demand of the HVAC system. The energy saving from the HVAC system can only reach an optimum if the building is well-insulated. Therefore, the performance of the building insulation, windows and HVAC is discussed together.

Heating loss of buildings occurs mainly through external walls, roofs and windows. Therefore, the heat transfer coefficient (or U-value) of these three parts is calculated based on the local standard, Design Standard for Energy Efficiency of Public Buildings (DB33/1036-2007) (UAD, ZIAD & CMA 2007). The calculation results are illustrated in Table 8.2, and the calculation details are in Table E1-1 and E1-2 in Appendix E1.

Table 8.2. Heat transfer coefficient of walls, roofs and windows of the case building

		Heat transfer coefficient before retrofitting (W/m^2•K)	**Standard for level II public buildings in Zhejiang (W/m^2•K)**
External walls		2.029	≤1.0
Roofs		3.356	≤0.7
Windows	Steel frames	5.000	≤4.7 for east- and north-facing windows ≤3.5 for west- and south-facing windows
	Plastic steel frames	6.600	
Note		The calculation can be found in Table E1-1 and E1-2 in Appendix E1	Source: Design Standard for Energy Efficiency of Public Buildings (DB33/1036-2007) (UAD, ZIAD & CMA 2007)

The existing external walls are built with mortar, clay bricks, and tiles without insulation. Some parts of the tiles have been found to be hollow or peeling, leading to fast heat loss. The current heat transfer coefficient of external walls is 2.029 W/(m^2•K), which is over the benchmark of the local standard (UAD, ZIAD & CMA 2007) of no more than 1.0 W/(m^2•K). For existing roofs, there is a prefabricated insulation panel installed. However, it has not been upgraded since the building was built, and is broken and does not perform as insulation anymore. Currently, the U-value of existing roofs is about 3.356 W/(m^2•K), which is much over the benchmark of 0.7 W/(m^2•K) (UAD, ZIAD & CMA 2007). For windows, most existing windows are single glazing (3 mm thickness) with steel frames. Some of them were changed to PVC frames when the leaking problem was noticed. The U-value of existing windows with steel frames is 6.6 W/(m^2•K), and 5 W/(m^2•K) for those with PVC frames. However, both are beyond the value of the local standard as Table 8.2 shows.

The consequence of poor insulation and windows is the over-dependency on HVAC. A study by Zhu et al. (2009) analysed the relation between HVAC types and the energy consumption of public buildings in Hangzhou. It showed that, for public buildings of a similar scale, the electricity consumption by reverse cycle and varied refrigerant volume air conditioning system is similar, and the central air conditioning system may cause more consumption. The reverse cycle air conditioning system was only installed about five years ago for the case building. The power of cooling and heating is enough to adjust for indoor thermal comfort. Therefore, the HVAC system has little room for improvement to achieve energy efficiency.

Based on the above discussion, the massive energy consumption by the HVAC system is mainly because the building does not have insulation leading to fast heating loss. To maintain indoor thermal comfort, the air conditioning must work with full power during its whole working period in winter and summer. The climate in Hangzhou city is hot in summer and cool in winter. The indoor temperatures in spring and autumn are good enough without using HVAC (Zhu et al. 2009). For the case building, the average indoor temperature is about 28 ℃ in summer and 18 ℃ in winter. However, based on the local standard (UAD, ZIAD & CMA 2007), the comfortable indoor temperature with intervention by HVAC should be in the range of 24 ℃ to 26 ℃ in summer and 22 ℃ to 24 ℃ in winter. To reach the target temperature, HVAC is needed to make the indoor temperature 2 to 4 ℃ cooler in summer and 4 to 6 ℃ warmer in winter.

(2) Inefficient lighting system

The current bulbs are T8 fluorescent with a power of 32W (Jappha 2018). There are 2,900 bulbs in the building. Assuming 8 hours in a working day and 250 working days per year, the lighting system consumes about 185,600 kWh electricity per year. The local standard (UAD, ZIAD & CMA 2007) regulates that, for office buildings, the lighting power density should be equal to or less than 11 W/m^2, and the illuminance value should be around 300 lx. There are other bulb types that can provide enough illuminance but with less electricity demand. Due to the large number of bulbs in use, even if little electricity can be saved by each bulb, the potential for electricity saving is still great by changing the bulb type to a more energy efficient one, such as T5 and LED. Moreover, the lighting can only be controlled manually. People often forget to turn off lights when they leave the room, resulting in the waste of electricity.

(3) Inefficient lifts

There are four lifts in the building. They were installed when the building was first built, which makes the lifts energy consuming and slow compared to new types. Records show that the annual electricity consumption of these four lifts is 18,363 kWh. There is a lack of regulation or standard that can provide a benchmark of acceptable electricity consumption by lifts. However, according to the study by Zhang, Ni and Nu (2009), the application of energy-efficient lifts in China may achieve 20% to 50% energy saving compared to conventional lifts.

(4) No renewable energy in use

Nowadays, solar energy is encouraged by the government and is widely used in China. The local government in Hangzhou also encourages the use of solar energy because of the adequate solar light and relatively long daytime compared to northern China. However, there is no renewable energy in use in this building, leading to the heavy reliance on electricity energy.

(5) Lack of building management control system (BMCS)

The air conditioning in the case building can only be controlled manually, so waste can be easily caused by people forgetting to turn the system off when they leave the room or when the indoor temperature is the same as the outdoor temperature. Moreover, without an energy consumption monitoring system installed, which is one type of BMCS, it is difficult to notice an abnormal use, leading to waste as well.

8.2.1.2. Excessive water consumption

Over the previous three years, the average annual water consumption of the building is about 23,970 kL for the 1000 tenants in the building. Therefore, yearly water consumption is about 24 kL per person, which is beyond the design limit for office buildings of 11~18 kL per person (MOHURD 2019). By checking the current water system, the problems below are identified, which lead to excessive water consumption.

(1) Old water fixtures, with 86 old flush toilets in total. Water tanks provide no pressure, and 9 L of water is needed for each use. There are 200 old taps (screw type lifting cast iron faucet) with slow water output.

(2) No water treatment system is installed. About 30 kL tap water is used for car washing per month, and 2 kL tap water is used to irrigate plants. In addition, tap water is also used for regular cleaning, such as floor cleaning. If a water treatment system is installed for treating greywater and stormwater, treated water can be used for car washing and irrigation, contributing to water saving.

8.2.1.3. Poor indoor visual comfort

The indoor thermal, acoustic and visual comfort of the case building are investigated in the case study. There were no complaints about indoor thermal performance collected from tenants, mainly because the climate in this region (hot-summer-cold-winter) is relatively mild compared to the climate in northern China. As discussed in Section 8.2.1.1, the U-value of the existing external walls, roofs and windows cannot meet the requirement of the local standard. However, the operation of HVAC can adjust the indoor temperature to a comfortable level. Therefore, it is expected that with the improvement of insulation performance of building envelopes, the indoor comfort level will not be reduced with less or no HVAC intervention.

To test indoor acoustic performance, a test of background noise was conducted at an office room and a meeting room at a low (floor level 2), medium (floor level 5), and high (floor level 12) level respectively. A real-time signal noise sensor (Model type: AWA2691) was used to test background noise. The duration of each test is 20 minutes with 0.1s sampling interval. The average value of all the samplings was taken as the background noise of the tested room. The test results are shown in Table 8.3. The standard value of background noise for office rooms and meeting rooms is 45 dB based on the national standard, Code for Design of Sound Insulation of Civil Buildings (GB50118-2010), which should not be exceeded (MOHURD

2010). All the test results meet the requirement. Therefore, the indoor acoustic performance of the case building can be regarded as acceptable.

Table 8.3. Test of background noise of the case building

Floor level	Room type	Background noise (dB)	Standard value (dB)
Level 2	Office room	40.3	≤ 45
	Meeting room	38.4	
Level 5	Office room	43.5	
	Meeting room	43.1	
Level 12	Office room	42.6	
	Meeting room	39.2	
Note	Measurement is based on the Code for Design of Sound Insulation of Civil Buildings (GB50118-2010), which should not be exceeded (MOHURD 2010)		

The case building is constructed with single-glazing windows (1.8m × 1.8m) and no internal blinds or external shading devices are installed. In addition, based on the information provided by building managers, the designed illuminance of existing lighting bulbs meets the required value (300 lx) by the standard of Zhejiang province, Design Standard for Energy Efficiency of Public Buildings (UAD, ZIAD & CMA 2007). Regarding the tenant complaints about the intensive sunlight (see the beginning of Section 8.3.1), a problem of the case building is the intensive sunlight shining from the south at certain moments. Therefore, retrofitting is an opportunity to solve this problem.

8.2.1.4. High operation cost

The operation cost of the case building is mainly for electricity and water usage. The operation cost is highly related to the electricity and water efficiency of the building. Due to the diagnosed problems of high energy consumption and excessive water consumption, there is a big potential for saving operation cost by improving the efficiency of electricity and water. Based on the electricity and water bills in the past three years, the annual operation cost of the building is about CNY 1,186,953, which is about AUD 262,869 based on the currency rate in 2022 (AUD 1 ≈ CNY 4.55).

Based on the identified problems and demands of building owner, facility managers, and tenants, the retrofitting goals and project constraints of the case study are identified:

- Two retrofitting goals are defined:
    1. to achieve at least a 30% reduction in annual operation cost
    2. to obtain a national green building label
- Two retrofitting objectives are identified:
    1. to reduce operation cost by increasing the energy efficiency of building service systems
    2. to reduce operation cost by decreasing the energy demand of the case building
    3. to reduce water cost by increasing the water efficiency of water fixtures
    4. to reduce water consumption by reusing treated greywater and stormwater for car washing, irrigation and cleaning
    5. to improve indoor visual comfort by glare control

- Project constraint is:
    1. The budget of the retrofitting project is CNY 3 million (AUD 659,341).

8.2.2. Develop retrofitting activities

Based on the problems identified, reference to locally applicable retrofitting activities (in Table 7.18 of Chapter 7), and consultation with local professionals in construction and property management sector, the following ten retrofitting activities are identified for the case building (see Table 8.4).

8.2.2.1. Improve insulation performance of external walls and roofs

The local standard, Design Standard for Energy Efficiency of Public Buildings (DB33/1036-2007) (UAD, ZIAD & CMA 2007), includes information about recommended insulation design for local buildings, which is usually used as a design guide. By consulting with local professionals in construction and property management and combining the information from the local standard, an EPS system is selected as insulation for external walls, an XPS system is selected for roofs, and low-e double-glazing windows (5 mm thick low-e glass plus 5 mm thick normal glass with air filling in between) with aluminium frames are selected. These insulation materials are also selected because they are locally available, which can save cost and time on transport. The initial cost of upgrading insulation of external walls and roofs is about CNY 771,376, and it is CNY 710,088 to replace existing windows with low-e double-glazing windows. Detailed information about type, thickness, and amount of insulation materials for external walls, roofs and windows is in Table E2-1 in Appendix E-2. The calculation of the heat transfer coefficient of the selected insulation materials of external walls, roofs and windows shows that they can meet the requirement of the local standard, DB33/1036-2007 (UAD, ZIAD & CMA 2007), as Table E1-1 and Table E1-2 (in Appendix E-1) show.

In addition, adopting a green roof can also improve the insulation performance of roofs. Extensive roofs can mitigate the cooling energy of buildings by 1.3% to 13.3% (Aboelata 2021). However, the initial cost of a green roof of about CNY 500/m^2 based on quotes from local companies engaging in green roofing[1] is too high. It may cost CNY 650,000 (about 22% of the project budget) if the whole roof area of about 1300 m^2 is constructed as a green roof. In addition to the high initial cost, the maintenance cost of green roofs is also very high. The high construction and maintenance cost is the biggest obstacle to implementing green roofs in China (Dong, Zuo & Luo 2020). Considering the limited amount of energy saving, and the relatively high costs, a green roof is not considered for the case building.

8.2.2.2. Improve energy efficiency of lighting system

Two activities can be adopted to improve the energy efficiency of the lighting system: installing motion sensors and changing existing bulbs to more energy efficient ones. Installing motion

Note 1: The link of the local supplier of green roof: http://www.cnwen.net/article/article_show/560194/

sensors can turn off lights automatically when motion cannot be detected for a certain time, which helps achieve about a 30% energy reduction on the lighting system (Riyanto et al. 2018). In addition, the cost of motion sensors is about CNY 78 each, and 900 motion sensors are needed (see Table E2-1 in Appendix E-2). Therefore, the retrofitting activity may cost about CNY 702,200 at the retrofitting stage.

The current bulb type is T8 fluorescent. There are several bulb types that are more energy efficient than T8 fluorescent, such as T5 and LED. However, the life of T5 bulbs is normally shorter than T8 bulbs. Moreover, by removing existing T8 fluorescent bulbs, T8 LED tube can be easily installed and operated since existing electronic ballast of T8 fluorescent is also applicable for T8 LED. The cost of one T8 LED bulb is about CNY 28.9 according to local suppliers. Therefore, T8 LED is selected to replace the existing T8 fluorescent bulbs. The power of a T8 LED is about 17W, while it is 32W for a T8 florescent bulb (Jappha 2018). About 2900 bulbs need to be replaced. Therefore, changing existing bulbs to T8 LED is expected to achieve substantial energy saving.

8.2.2.3. Improve energy efficiency of lifts

The current lifts are energy consuming and slow. New types of lifts with a regeneration system can convert motion power to electricity to support the operation of lifts, resulting in electricity saving. Based on studies by Al-Kodmany (2015), Ali et al. (2021), Carrillo et al. (2013) and Nguyen (2017), changing traditional lifts to energy efficient ones can help reach energy saving of lifts by 30%. There are several lift companies in the local area that can provide transport, installation and maintenance service. The cost of one energy efficient lift is about CNY 656,348 based on the quote by the local suppliers. Even though the initial cost of energy efficient lift is relatively higher than other proposed retrofitting activities, the brought benefits in environmental and social dimensions such as improved energy efficiency and more efficient traffic flow (see Section 3.4.5 in Chapter 3) still make it worthy to be considered for the case building.

8.2.2.4. Install PV panels

China is a world leader in PV module production, accounting for approximately 64.5% of global output in 2018 (Yu & Tong 2021). In 2019, the cumulative PV power generation installed capacity in China reached 204.7 GW, accounting for 32.6% of the world's total installed capacity (Yu & Tong 2021). The technology and practice of installing PV panels to reduce reliance on fossil fuel is available and common in China. There are several local suppliers who can provide transport, installation and maintenance service, making installing PV panels a feasible retrofitting activity for the case building. Based on the quote by local suppliers, about CNY 698 is needed to install one PV panel. Considering the relatively high price of per unit and limited roof area available, it is designed that 50 PV panels are installed by the retrofitting. The power of each PV panel is about 300W, and the efficiency rate is 75% according to the information provided by the local suppliers. The designed annual electricity generation is about 20,531 kWh.

8.2.2.5. Improve energy efficiency of HVAC

As discussed in Section 8.3.1.1, there is no BMCS installed in the case building, leading to additional energy consumption due to waste. There is an energy consumption monitoring platform available in Zhejiang province (Li et al. 2020). By installing monitoring meters, the monitoring platform can automatically record energy consumption by different building service systems and report any abnormal use in real-time to avoid waste (Li et al. 2020). The initial cost of the monitoring system is about CNY 270,000 based on the quotes by local suppliers, which is about 9% of the project budget. Therefore, it can be considered for the case building.

8.2.2.6. Improve indoor visual comfort

There is no external shading panels or internal blinds installed in the case building, leading to poor indoor visual comfort. Retrofitting is an opportunity to fix the problem. The service life of window blinds is estimated to be about 10 years (EATS 2015), while it is about 25 to 30 years for external shading devices (Penny 2015). In addition, regular maintenance such as cleaning and repair is needed for internal blinds, but is barely required for external sun shading panels if the fixed shading devices (without automatic angle adjustment) are adopted. In addition, sun shading devices can also contribute to a reduction of about 9% of energy consumption by the HVAC system (Valladares-Rendón, Schmid & Lo 2017). The common practice in the local area is adding aluminium sun shading slats (as in Figure 8.2) for windows facing south which get intensive sunlight. The cost of aluminium sun shading slats is about CNY 550 per metre square. To install sun shading slats on windows facing south, about CNY 249,480 is needed. Therefore, aluminium sun shading slats will be added on windows facing south to control indoor glare.

Figure 8.2. Aluminium sun shading slats

Source: Achiexpo 2022

8.2.2.7. Improve water efficiency

Three retrofitting activities are available to improve water efficiency of the case building: installing water control sensors, replacing existing water fixtures with water efficient ones, and installing a water treatment system to recycle greywater and stormwater. Automatic control sensors for taps can turn off taps automatically when the handle is released, or in a set time (such as 30 seconds) to avoid waste (Nguyen 2017). However, the existing taps and toilets in the building are outdated, and cannot provide the required flow rate. The prices of water-saving taps and toilets are reasonable, at about CNY 55 for one tap and CNY 550 for one toilet. Therefore, replacing existing water fixtures with water efficient ones is a better solution to the inefficient water use compared to installing water control sensors.

Treating and recycling greywater and stormwater by installing a water treatment system can save up to 50% of water use in an office building (Friedler & Alfiya 2010; Nguyen 2017). There is an above-ground box-type integrated water treatment plant available in the local area which can be easily installed and operated to recycle greywater and stormwater. The initial cost of the water treatment plant is about CNY 31,900 (about 1% of the budget) based on the local suppliers. Therefore, installing a water treatment system can be considered for the case building.

Based on the above discussion, ten retrofitting activities are identified for the case building as Table 8.4 summarises. To save time, expense and energy caused by transport, the materials and products needed for the retrofitting will be purchased locally or from neighbouring provinces, such Shanghai and Suzhou. Therefore, the specification information of required materials and products provided by local suppliers is used in the case study. Details and references for the adopted materials and products in this case study are in Table E2-1 in Appendix E-2.

Table 8.4. Proposed retrofitting activities for the case building

Problems	Possible reasons	Retrofitting activities
High energy consumption	Poor insulation of building envelopes	• Install/upgrade insulation of building envelopes (EPS for walls and XPS for roofs) • Replace existing windows with double glazed windows with low-e coat and aluminium frames
	Inefficient lighting system	• Install motion sensors • Change from T8 fluorescent to T8 LED light bulbs
	Inefficient lifts	• Change existing lifts to energy efficient lifts
	No renewable energy in use	• Install photovoltaic system (PV panels)
	Lack of energy consumption monitoring system	• Install building energy consumption monitoring system
Excessive water consumption	Inefficient sanitary fixtures	• Replace existing taps and flush toilets with water-saving ones
	No water treatment system	• Add water treatment system for recycling greywater and stormwater
Poor indoor visual comfort	No sun shading devices installed	• Add aluminium sun shading slats
High operation cost	Same as high energy consumption and water consumption	Same as high energy consumption and water consumption

8.2.3. Develop assessment criteria

The assessment criteria suitable for local use are also developed in the operating model, as Table 7.19 in Chapter 7 shows. The identified assessment criteria are used to estimate the performance of potential retrofitting activities. However, some of the identified assessment criteria are not included in this case study for the following reasons.

First, the embodied energy and embodied carbon emissions of newly added building materials and building service systems need to be measured. Plenty of studies have measured the embodied energy and embodied carbon emissions of building materials, such as concrete, cement, glass, steel, etc., for which the associated embodied energy and embodied carbon coefficients are available. As for building service systems, such as building management control system, lifts etc., they are made of various materials and have a complicated manufacturing process, leading to complex computations. However, compared to building materials, the embodied energy and embodied carbon emissions of building service system are minor. For example, the weight of insulation materials of external walls added in the case study is about 291 tonnes, but the weight of installed lifts is only 1,344 kg. Therefore, the embodied energy and embodied carbon emissions of lighting motion sensors, lifts, the building energy consumption monitoring system, and the water treatment plant is not calculated in this study.

Second, as discussed in Section 8.2.2, local suppliers of building materials and building service systems are considered over those in other provinces, so there will be very little energy consumption by transporting building materials and products from the supplier to the construction site.

Third, as discussed in Section 6.7.1.1 (in Chapter 6), due to the small amount and uncertain estimation of waste generation by operating and maintaining the upgraded building materials and service system, only waste generation by replacing broken or obsolescent building materials and service systems is considered in this case study.

Fourth, maintenance cost and cleaning cost need to be calculated in LCC. However, the purpose of LCC in this study is to measure and compare the improvement level of economic performance by the proposed retrofitting activities, which can be used to select suitable ones. There are regular expenditures on maintaining and cleaning the case building, even though retrofitting is not conducted. Therefore, the difference in maintenance cost and cleaning cost by retrofitting activities is expected to be minor compared to the difference in operation cost.

Based on the above discussion, it is determined that the embodied energy and carbon emissions of lighting motion sensors, lifts, the building energy consumption monitoring system, the water treatment plant, and waste generation by operating and maintaining building service systems are not considered in this case study. Moreover, if one estimation is less than 1% of the total amount for one assessment criterion, it is neglected in the case study. For example, the energy consumption by transporting lifts from the supplier to the construction site is less than 1% of the total energy consumption by lifts in the retrofitting and operation stage. Therefore, it will not be included. The finalised assessment criteria for this case study are listed in Table 8.5.

Table 8.5. Assessment criteria for the case study

Sustainability dimension	**Life cycle stage**	**Assessment criteria**	
Environmental dimension	Retrofitting stage	Energy consumption	Embodied energy of added building materials
			Energy consumption by retrofitting construction
		Carbon emissions	Embodied carbon emissions of added building materials
			Carbon emissions by retrofitting construction
		Potential for reuse/recycling of materials	
	Operation stage	Energy consumption	Recurrent embodied energy of added building materials
			Energy consumption by operation activities
		Carbon emissions	Recurrent embodied carbon emissions of added building materials
			Carbon emissions by operation activities
		Potential for reuse/recycling of materials	
		Waste generation from replacement	
		Indoor visual comfort	
		Water consumption by operation activities	
Economic dimension	Retrofitting stage	Initial cost	
	Operation stage	Operation cost	
		Replacement cost	
Social dimension	Retrofitting stage	Noise impact on neighbourhood	
		Emission impact on neighbourhood	
		Safety of retrofitting construction	
		Impact on cultural heritage	
		Impact on surrounding traffic and pedestrians	
		Impact on relocating tenants	
	Operation stage	Accessibility to building facilities for people with special needs	
		Accessibility to building services (such as automatically adjusted indoor temperature, humidity, and dimming level by BMCS)	
		Impact on maintenance and maintainability from newly added building fabrics and building systems	
		Impact on safety and security of users	
		Room flexibility for different users	

8.2.4. Evaluate performance of retrofitting activities

The environmental, economic and social performance of the proposed retrofitting activities is evaluated against the developed assessment criteria.

8.2.4.1. Environmental impact assessment

The cradle-to-use boundary system is adopted, in which the production stage, retrofitting construction stage, and operation stage are included. The 50-year remaining service life is assumed as the study period. For environmental assessment, two kinds of data were collected:

- Material data (see Table 8.6), such as the quantity of materials used in the retrofitting stage. Quantities are measured based on drawings of the case building, regulations from related national or local standards, and consulting with local professionals. Details are in Table E2-1 in Appendix E-2.
- Equipment data (see Table 8.7), including quantity, type and capacity of equipment in the construction and operation stages. This information is determined based on the amount of construction and consulting with local professionals. As noted, energy and carbon for the manufacturing of construction tools, equipment and plants are excluded from the study. Details about equipment data are in Table E2-2 in Appendix E-2.

Table 8.6. Materials data for retrofitting the case building

Part of building	**Retrofitting activity**			**Materials**		**Amount**	**Unit**
External walls and roofs	A1	Install/upgrade insulation of building envelopes	External walls (EPS system)	Cement mortar with interface agent (cement:sand = 1:3)		275,223.6	kg
				EPS board		17,487	pieces
				Alkali resistant fibreglass mesh		37.77	m^3
				Waterproof paint		18.89	m^3
			Roof (XPS system)	Concrete (30MPa with fine stone) (Containing ø4@200 cold-drawn steel wire)	Steel mesh	1,500	kg
					Concrete (C30)	52	m^3
				Asphalt felt		65	rolls
				Cement mortar (cement:sand = 1:3)		52,000	kg
				XPS board		1,806	pieces
				Styrene butadiene styrene (SBS) modified bituminous sheet materials		130	rolls
Windows	A2	Change existing single glazing windows to low-e double glazing with aluminium frames		Glass		29.59	m^3
				Aluminium frames		913	frames
	A3	Add aluminium sun shading slats for windows facing south		Aluminium sun shading slats		280	panels
Lights	A4	Install motion sensors				900	pieces
	A5	Change from T8 fluorescent bulbs to T8 LED				2,900	bulbs
Lifts	A6	Change the existing lifts to more energy efficient ones				4	lifts
Energy supply	A7	Install PV panels				50	panels
BMCS	A8	Install building energy consumption monitoring system				1	system
Water system	A9	Change existing taps and toilets to water-saving ones		Change existing water taps to water-saving taps		200	taps
				Change existing toilets to water-saving toilets with high pressure water tanks		86	toilets
	A10	Install water treatment system to recycle greywater and stormwater				86	item

(1) Energy consumption and carbon emissions

In the retrofitting stage, the quantity, power and running hours of required construction equipment for different retrofitting activities are estimated based on the amount of construction work shown in Table E2-1 in Appendix E2. Most of the required equipment consumes electricity, but some equipment consumes diesel, such as the autocrane and concrete pump truck. Based on the local regulation, General Rules for Calculation of the Comprehensive

Energy Consumption (GB/T2589-2020) (SAMR & SAC 2020), the coefficient of converting diesel to electricity is 11.86 kWh/kg, and this figure is adopted to convert diesel consumption to electricity. As for the carbon emissions, the carbon emission intensity of electricity generation is 0.81 kg CO_2/kWh for Zhejiang province in 2016 (Ding & Ying 2019). According to Cheng and Yao (2021) and Zheng, Song and Shen (2021), carbon emission intensity in China decreases by 0.028% to 0.043% for every 1% increase in the innovation level of renewable energy development. Therefore, the value in the current year (2022) is supposed to be less than 0.81 kg CO_2/kWh. However, no later data than 2016 can be identified for Zhejiang province. Therefore, the figure in 2016 is adopted in this case study to calculate carbon emissions caused by the proposed retrofitting activities, and the calculated carbon emissions are expected to be the maximum value. The detailed calculation can be found in Table E2-2 in Appendix E-2. The type of required construction equipment and calculation results are illustrated in Table 8.7.

Table 8.7. Energy consumption and carbon emissions by operating construction equipment

Part of building	**Retrofitting activities**			**Electrical equipment**	**Energy consumption (MJ)**	**Carbon emissions (kg CO_2)**
External walls and roofs	A1	Install/upgrade insulation of building envelopes	External walls (EPS system)	Electric suspended platform	65,201.00	14,670.00
				Rotary hammer		
				Mortar mixer		
			Roof (XPS system)	Rebar cutting machine	21,656.00	4,872.61
				Bar straightening machine		
				Tapered reverse tilting concrete mixer		
				Mortar mixer		
				Autocrane		
				Concrete pump truck		
Windows	A2	Change existing single glazing windows to low-e double glazing with aluminium frames		Electric suspended platform	4,140.00	931.50
Sun shading	A3	Add aluminium sun shading slats for windows facing south		Autocrane	42,822.60	9,635.10
				AC arc welder		
Lights	A4	Install motion sensors		Mobile elevator	2,430.00	546.75
	A5	Change from T8 fluorescent bulbs to T8 LED		Mobile elevator	3,920.00	882.09
Lifts	A6	Change the existing lifts to more energy efficient ones		Electric winch	2,484.00	558.90
Energy supply	A7	Install PV panels		Autocrane	21,275.78	4,764.55
				AC arc welder		
BMCS	A8	Install building energy consumption monitoring system			/	/
Water system	A9	Change existing taps and toilets to water-saving ones			/	/
	A10	Install water treatment system to recycle greywater and stormwater		Autocrane	634.80	142.83
				Electric single stage centrifugal water pump		

In addition, embodied energy (EE) and embodied carbon (EC) emissions of the used building materials are also calculated for the retrofitting stage. The source of data for energy intensity and carbon emission coefficient of building materials in China is adopted from research studies by Wang (2009), Yan (2011), Li et al. (2013), Li (2015), Zhang and Wang (2016), Cang et al. (2020), Zhu et al. (2020) and Chen et al. (2022). However, these studies cannot provide all required data for this case study. In China, there is not a comprehensive database for embodied energy and embodied carbon, which can cover all types of construction materials. Therefore, data from outside of China is widely used as proxies for research purposes. In this case study, the database Inventory of Carbon and Energy (ICE) (Hammond & Jones 2011) and several other studies from other countries including Alstone, Mills and Jacobson (2011), AUSTEP

Lighting (2015), Koezjakov et al. (2018), Robati, Daly and Kodogiannakis (2019), Resalati, Kendrick and Hill (2020) and Ahmed et al. (2021) are used as supplements. The detailed calculation and source of data adoption are in Table E2-3 in Appendix E-2. The calculation results for embodied energy and embodied carbon emissions are presented in Table 8.8.

Table 8.8. Embodied energy (EE) and embodied carbon (EC) emissions of installed building materials

Part of building	**Retrofitting activities**			**EE (MJ)**	**EC emissions (kg CO_2)**
External walls and roofs	A1	Install/upgrade insulation of external walls and roofs	External walls	1,205,186.18	104,351.23
			Roofs	629,312.44	80,951.33
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames		1,886,920.94	232,414.01
	A3	Add aluminium sun shading slats for windows facing south		324,800.00	106,288.00
Lights	A5	Change from T8 fluorescent bulbs to T8 LED		124,700.00	6,690.00
Energy supply	A7	Install PV panels		394,871.40	24,157.98
Water system	A9	Change existing taps and toilets to water-saving ones	Taps	40,000.00	2,240.00
			Toilets	15,609.00	1,006.20

In the operation stage, the electricity consumption by operating electricity-related service systems is estimated. It can be evaluated by using simulation tools. However, it is time-consuming and expensive. Considering the time constraint of this study, the saving potential by proposed retrofitting activities in existing research studies is adopted in this study. As for carbon emissions in the operation stage, according to the study by Ding and Ying (2019), the carbon intensity of electricity generation is 0.81 kg CO_2/kWh for Zhejiang province. This figure is adopted to evaluate the carbon emissions in the operation stage in this case study. The detailed calculations are in Table E2-4 in Appendix E-2, and the estimation results are illustrated in Table 8.9.

Table 8.9. Evaluation results of annual energy consumption and carbon emissions of building service system after retrofitting

Upgraded building service systems	**Retrofitting activities**		**Annual electricity consumption by the building service system**		**Annual carbon emissions by the building service system**	
			Before retrofitting (MJ)	**After retrofitting (MJ)**	**Before retrofitting (kg CO_2)**	**After retrofitting (kg CO_2)**
HVAC	A1	Install/upgrade insulation for external walls and roofs	1,454,319.50	581,727.80	402,765.66	206,432.53
	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames		1,289,981.40		365,789.59
	A3	Add aluminium sun shading slats for windows facing south		271,876.90		373,315.69
Lights	A4	Install motion sensors	2,644,217.30	1,850,952.10	732,301.20	553,816.53
	A5	Change from T8 fluorescent bulbs to T8 LED		2,331,017.28		661,831.20
Lifts	A6	Change the existing lifts to more energy efficient ones	66,105.43	46,273.80	18,307.53	13,845.41
Energy supply	A7	Install PV panels	/	-73,377.03	/	-16,509.83
BMCS	A8	Install energy consumption monitoring system	/	-158,653.04	/	-35,696.93
Water system	A9	Change existing taps and toilets to water-saving ones	/	/	/	/
	A10	Install water treatment system to recycle greywater and stormwater		6750.00	/	1,518.75

Note: The negative symbol "-" represents energy saving or carbon emission reduction by retrofitting activities.

In addition, the recurrent embodied energy (REE) and embodied carbon (REC) emissions by replacing building materials during the operation stage is estimated based on initial EE and EC emissions of newly added building materials and required replacement frequency. The detailed calculation is in Table A2-5 in Appendix A2, and the estimation results are presented in Table 8.10.

Table 8.10. Recurrent embodied energy (REE) and embodied carbon (REC) emissions in the operation stage

Part of building	**Retrofitting activities**			**REE (MJ)**	**REC emissions (kg CO_2)**
External walls and roofs	A1	Install/upgrade insulation of external walls and roofs	External walls	2,410,372.36	208,702.46
			Roofs	1,384,624.88	161,902.66
Windows	A2	Replace existing single-glazing windows with low-e double glazing with aluminium frames		3,773,841.88	464,828.00
	A3	Add aluminium sun shading slats		324,800.00	106,288.00
Lights	A5	Change from T8 fluorescent bulbs to T8 LED		124,700.00	6,960.00
Energy supply	A7	Install PV panels		394,871.40	24,157.98
Water systems	A9	Change existing taps and toilets to water-saving ones	Taps	/	/
			Toilets	31,218.00	2,012.40

By summarising the estimation undertaken above, the difference (extra consumption or saving compared to the consumption before retrofitting) on energy consumption and carbon emissions by the proposed retrofitting activities can be obtained as Table 8.11 shows. More detailed calculation of total energy consumption and carbon emissions by the proposed retrofitting activities is in Tables E2-6 and E2-7 in Appendix E-2.

Table 8.11. Difference in energy consumption and carbon emissions by retrofitting activities

Part of building	**Retrofitting activities**		**Difference on retrofitting stage**		**Difference on operation stage (50 years)**		**Total difference by retrofitting activities (50 years)**	
			Energy consumption (MJ)	**Carbon emissions (kg CO_2)**	**Energy consumption (MJ)**	**Carbon emissions (kg CO_2)**	**Energy consumption (MJ)**	**Carbon emissions (kg CO_2)**
External walls and roofs	A1	Install/upgrade insulation for external walls and roofs	1,984,335.62	204,845.56	-39,834,587.80	-9,446,051.40	-37,850,232.14	-9,241,206.21
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames	1,891,060.90	233,345.51	-4,443,063.00	-1,383,975.50	-2,552,002.20	-1,150,629.99
	A3	Add aluminium sun shading slats for windows facing south	367,622.60	115,923.10	-6,219,638.00	-1,366,210.50	-5,852,015.40	-1,250,287.40
Lights	A4	Install motion sensors	2,430.00	546.75	-39,663,259.00	-8,924,233.50	-39,660,829.00	-8,923,686.75
	A5	Change from T8 fluorescent bulbs to T8 LED	128,620.00	7,842.09	-15,535,300.00	-3,516,540.00	-15,406,680.00	-3,508,697.91
Lifts	A6	Change existing lifts to more energy efficient ones	2,484.00	558.90	-991,581.50	-223,106.00	-989,097.50	-222,547.00
Energy supply	A7	Install PV panels	416,047.18	28,922.53	-3,273,980.10	-801,333.50	-2,857,932.92	-772,411.99
BMCS	A8	Install energy consumption monitoring system	/	/	-7,932,652.00	-1,784,846.50	-7,932,652.00	-1,784,846.50
Water system	A9	Change existing taps and toilets to water-saving ones	55,609.00	3,246.20	31,218.00	2,012.40	86,827.00	5,258.60
	A10	Install water treatment system to recycle greywater and stormwater	634.80	142.83	337,500.00	75,937.50	338,134.80	76,080.33

Note: symbol "-" represents energy saving or carbon emissions reduction

Table 8.11 shows that the proposed retrofitting activities cause extra energy consumption and carbon emissions in the retrofitting stage, while contributing to energy saving and carbon emission reduction in the operation stage. By compensating for the consumption and emissions in the retrofitting stage, the total energy saving and carbon emissions by the proposed retrofitting activities can be attained and are used to develop retrofitting strategies in later steps (in Section 8.3.6).

(2) Water consumption

Water consumption is evaluated for the operation stage only, including daily office use, car washing, and irrigation. The proposed retrofitting activities that may achieve water savings include A9 – Replace existing taps and toilets with water-saving taps (hob mount infrared sensor taps) and toilets (siphonix toilet with dual flush tank), and A10 – Install water treatment system for recycling greywater and stormwater.

The flow rate of existing taps is about 6 L/minute. The designed flow rate of the water-saving taps is about 4.5 L/minute. There are 200 taps installed in the building which need to be replaced. Assuming each tap works for about 10 minutes per working day and 250 working days per year, about 750 kL water can be saved annually by replacing water taps with water-saving ones. In addition, the existing toilets need about 9 L water for each flush, but the designed water use of the water-saving toilets is about 4.5 L water each flush. There are 86 toilets in total, and each toilet is used about 5 times per working day on average. Therefore, about 483.75 kL water can be saved annually by replacing existing toilets with water-saving toilets.

With water-saving taps installed, about 9 kL greywater will be generated per day based on the above assumptions. Assuming about 9 kL stormwater can be collected per month, there will be about 189 kL greywater and stormwater generated per month. According to Table A2-1 in Appendix A2, the designed water treatment speed of the water treatment plant is about 40 m^3/hour, and the treatment rate is 60%. Therefore, it is capable of recycling the 189 kL of greywater and stormwater per month, resulting in 1,361 kL annual water saving. The recycled water can be used for car washing, irrigation and cleaning as discussed in Section 8.2.1.2. The water saved by the retrofitting activities A9 and A10 is illustrated in Table 8.12.

Table 8.12. Evaluation results of water saving

Retrofitting activities			**Number**	**Original flow rate**	**Flow rate after retrofitting**	**Original annual water consumption by taps and toilets (kL)**	**Annual water consumption by water-saving taps and toilets (kL)**	**Annual water saving (kL)**	**Total water saving (in 50 years) (kL)**
A9	Change existing taps and toilets to water-saving ones	Taps	200	6 L/minute	4.5 L/minute	3,000.00	2,250.00	750.00	61,687.50
		Toilets	86	9 L/flush	4.5 L/flush	967.50	483.75	483.75	
A10	Install water treatment system to recycle greywater and stormwater		/	/	/	/	/	1,361.00	68,050.00

(3) Potential reuse or recycling of materials

The percentage of material use of each retrofitting activity that can be recycled for future use is estimated. The steel and concrete of insulation systems (retrofitting activity A1), glass and aluminium of windows (A2), aluminium of sun shading slats (A3), brass of water taps, and ceramics of toilets (A9) are materials that can be recycled or reused. The proportion of recyclable or reusable materials can be obtained by dividing the weight of the recyclable or reusable materials by the total weight of the added materials by the retrofitting activity. Moreover, based on the study by Franz and Wenzl (2017), about 20% of the weight of a LED bulb can be recycled. This figure is adopted to estimate the proportion of recyclable materials by retrofitting activity A5. For lifts and the water treatment plant, no data about recycling or reuse of them is available. However, removed lifts and water treatment plants are often disassembled, and most components can be recycled or reused, such as using them as spare components for repairs. Considering the finishes and lights in lift cars, and broken components, it is assumed that 90% of lifts and water treatment plants can be recycled or reused. As for the building energy consumption monitoring system, no information can be found to calculate the proportion of recyclable or reusable materials. The main components of the monitoring system are electricity meters, which are very light compared to other building materials and service systems applied in the case study. Therefore, it is neglected in this estimation. The estimation results are shown in Table 8.13. The detailed calculation is in Table E2-8 in Appendix E-2.

Table 8.13. Evaluation results on the use of reusable/recyclable materials

Part of building	Retrofitting activities		Recyclable/ reusable materials	% of recyclable/ reusable materials
External walls and roofs	A1	Install/upgrade insulation for external walls and roofs	• Steel wire • Concrete	27%
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames	• Glass • Aluminium	100%
	A3	Install aluminium sun shading slats for windows facing south	• Aluminium	100%
Lights	A4	Install motion sensors		0%
	A5	Change from T8 fluorescent bulbs to T8 LED	• Glass	20%
Lifts	A6	Change existing lifts to energy efficient ones	Whole lifts	90%
Energy supply	A7	Install PV panels		0%
BMCS	A8	Install energy consumption monitoring system		0%
Water system	A9	Change existing taps and toilets to water-saving ones	• Brass • Ceramics	100%
	A10	Install water treatment system to recycle greywater and stormwater	Whole water treatment plant	90%

(4) Waste generation

Waste generation in the operation stage is mainly from replacing broken or obsolescent building materials. They are estimated based on the designed service life, quantity, and weight of replaced building materials. Based on the above estimation of recyclable or reusable materials, the total waste generation by the proposed retrofitting activities can be estimated by multiplying the frequency of replacement during the operation stage with the amount of waste generation by replacement which the total weight of the added material minus the weight of the recyclable or reusable material by each retrofitting activity. The detailed calculation is in Table E2-9 in Appendix E-2, and evaluation results on waste generation are in Table 8.14.

Table 8.14. Evaluation results on waste generation

Part of building	**Retrofitting activities**			**Service life (years)**	**Total weight added by a retrofitting activity (kg)**	**Weight of recyclable or reusable materials (kg)**	**Total waste generation (kg)**
External walls and roofs	A1	Install/upgrade insulation for external walls and roofs	External walls	20	478,197	127,340	701,713
			Roofs	20			
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames		20	98,224	98,224	0
	A3	Install aluminium sun shading slats for windows facing south		30	112,200	112,200	0
Lights	A4	Install motion sensors		15	450	0	1,350
	A5	Change from T8 fluorescent bulbs to T8 LED		30	667	133	534
Lifts	A6	Change existing lifts to energy efficient ones		30	1,344	1210	134
Energy supply	A7	Install PV panels		30	1,125	0	1,125
BMCS	A8	Install energy consumption monitoring system		15	0	0	0
Water system	A9	Change existing taps and toilets to water-saving ones	Taps	50	400	400	0
			Toilets	20	1,376	1,376	0
	A10	Install water treatment to recycle greywater and stormwater		30	150	135	15

(5) Indoor environmental quality

Based on the discussion in Section 8.2.2.6, the main problem of indoor environmental quality is the poor indoor visual comfort due to intensive daylight. By changing single-glazing windows to double glazing with low-e coat and installing sun shading slats for windows facing the south, the situation can be improved. However, it is possible that the low-e coat and sun shading slats lead to insufficient interior daylight. Based on the Standard for Daylight Design of Buildings (MOHURD 2013), the daylight factor for office rooms and meeting rooms should be equal to or more than 2%. Daylight factor is designed as the standard value when meeting the requirements of visual function at the specified design illuminance of exterior daylight (450 lx for office buildings located in Zhejiang province) (MOHURD 2013).

Therefore, a simulation of interior daylight is conducted by using the simulation tool Ecotect, developed by Autodesk (Liu & Wang 2019). Ecotect is a commonly used simulation tool which can provide detailed environmental analysis of buildings, such as daylight radiation and spatial visibility, while providing visualisation analysis, such as images and line charts (Liu & Wang 2019).

According to the floor layout of the case building, the layout of Levels 1 to 4 is basically the same, and the layout of Levels 5 to 13 is basically the same, so in the modelling, Level 2 and Level 10 were selected for simulation, as Figure 8.3 and Figure 8.4 illustrate.

Figure 8.3. Layout of Level 2 of the case building

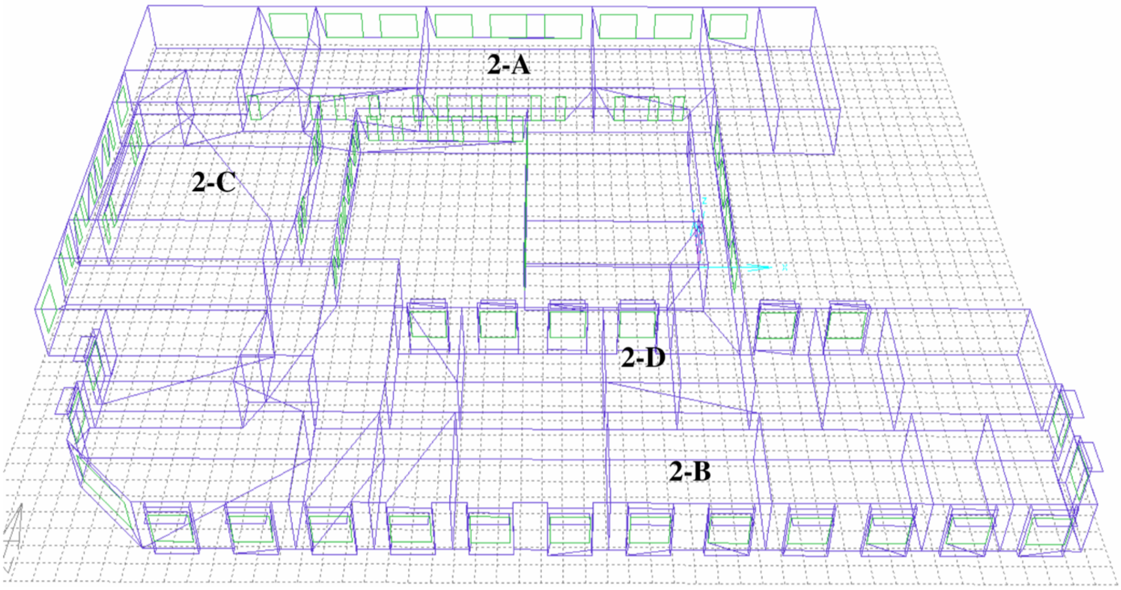
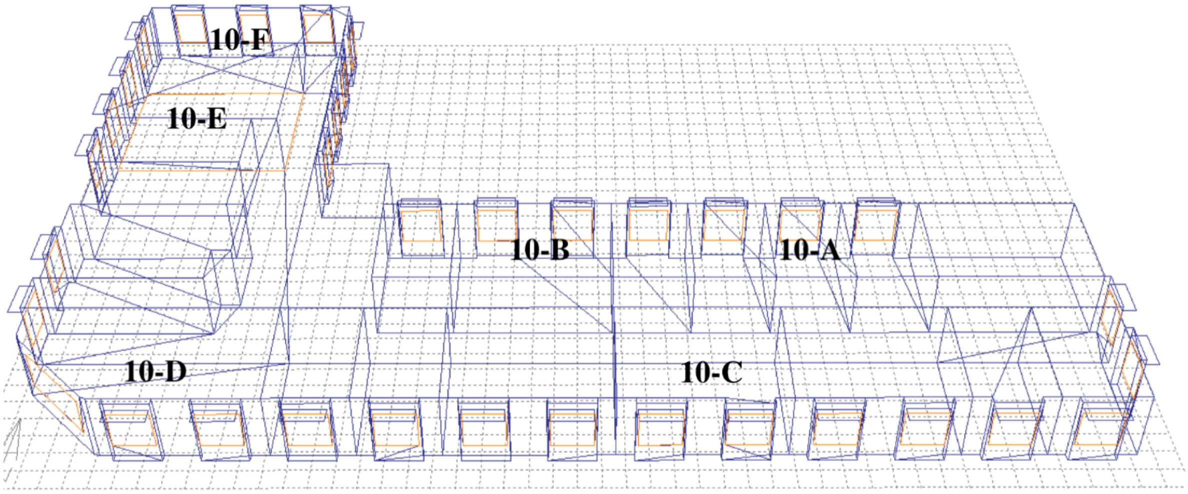


Figure 8.4. Layout of Level 10 of the case building



The simulation was conducted with the parameter settings illustrated in Table 8.15, according to the Chinese national standard, Standard for Daylighting Design of Buildings (GB 50033-2013) (MOHURD 2013).

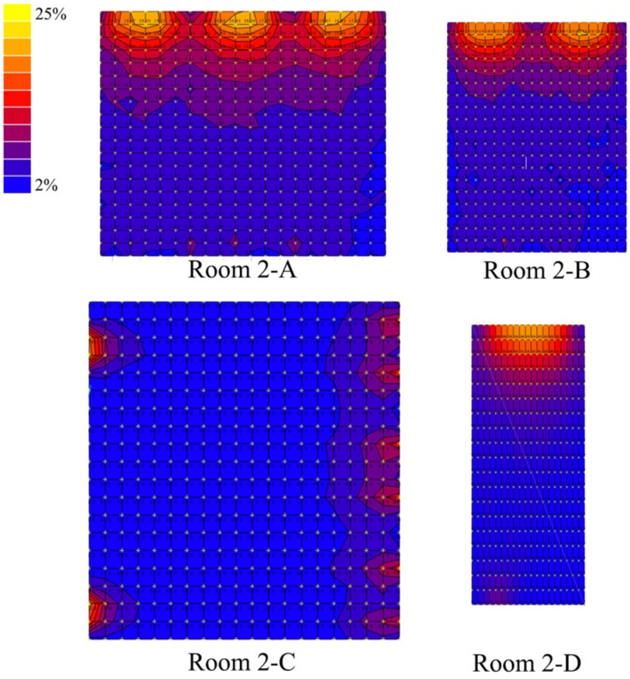
Table 8.15. Parameters for interior daylight simulation in Ecotect

Parameter	Definition	Input value
Phytoclimatic zone	Based on the range of total illuminance, China is divided into different phytoclimatic zone. Hangzhou is in phytoclimatic zone IV, where the design illuminance of exterior daylight is 13,500 lx.	IV
Critical illuminance of exterior daylight	Illuminance of exterior daylight when artificial lighting is required indoors	4500 lx
Reference surface	A surface in which illumination is measured or specified	0.8 m (measured from the floor)
Transmission ratio of windows	Ratio of transmitted luminous flux to incident luminous flux	0.8 (the value for low-e double-glazing windows with aluminium frames)
Standard value of interior daylight illuminance	Illuminance values on a reference surface corresponding to the specified design illuminance values for exterior daylight and the corresponding standard values for the daylight factor	450 lx (the value for office rooms and meeting rooms)
Reflectance ratio	The ratio of the reflected energy to the incident energy.	Internal wall (white painting): 0.75 Ceiling (white painting): 0.75 Floor (tile): 0.4 Glass: 0.08

Source: MOHURD 2013

The simulation results are shown in Figure 8.5, Figure 8.6 and Table 8.16. The results show that, with the implementation of retrofitting activities, changing window types and installing external sun shading slats, the daylight factor of the building is more than 2%, which can meet the requirement of the national standard (GB 50033-2013) (MOHURD 2013).

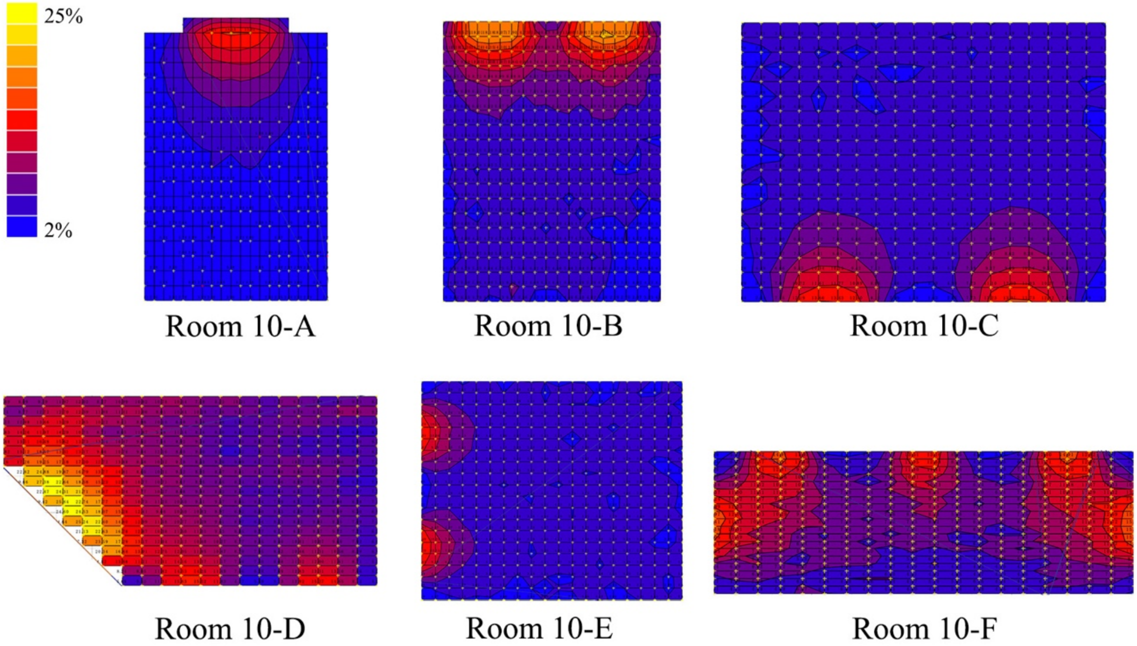
Figure 8.5. Ecotect simulation results of Level 2



Room 2-A Room 2-B

Room 2-C Room 2-D

Figure 8.6. Ecotect simulation results of Level 10



Room 10-A Room 10-B Room 10-C

Room 10-D Room 10-E Room 10-F

Table 8.16. Simulation results of interior daylight

Level	Room (in Figures 8.3 and 8.4)	Range of daylight factor	Limited value
Level 2	2-A	3.2%–23.2%	≥ 2%
	2-B	2.4%–22.4%	
	2-C	2.1%–22.1%	
	2-D	2.0%–21.4%	
Level 10	10-A	2.5%–21.8%	
	10-B	2.2%–21.8%	
	10-C	2.1%–21.5%	
	10-D	4.5%–24.5%	
	10-E	2.0%–21.2%	
	10-F	2.1%–22.1%	

As for indoor thermal comfort, it can be adjusted in an acceptable range by the use of HVAC. However, the retrofitting activity of install or upgrade insulation of building envelopes may contribute to keeping or improving indoor thermal comfort with less use of HVAC. The U-value of upgraded insulation for external walls, roofs and windows can be found in Tables A1-1 and A1-2 in Appendix A1, which are within the limit value of the local standard DB33/1036-2007 (UAD, ZIAD & CMA 2007). As for indoor acoustic performance, the background noise of the case building was tested (see Section 8.3.1.3), and it is within the limit value of the Chinese national standard (GB50118-2010) (MOHURD 2010), and no tenants complained about it. Therefore, no retrofitting activities are proposed for indoor acoustic performance.

Based on the discussion in Section 6.7.1.3 (in Chapter 6), only a pre-assessment of indoor environmental quality was conducted in this study to identify improvement areas for which potential retrofitting activities can be proposed. Combining the discussion in Section 8.2.1.3, it can be concluded that the problem of indoor environmental quality is mainly about indoor visual comfort due to intensive sunlight from the south. Two retrofitting activities may help mitigate the issue, changing existing single-glazing windows to low-e double glazing windows, and installing external sun shading slats. The simulation tool Ecotect was used to simulate the interior daylight of the case building with these two retrofitting activities implemented. The simulation results show that the daylight factor of the case building can meet the requirement of the Chinese national standard (GB 50033-2013) (MOHURD 2013). As for indoor thermal comfort and indoor acoustic comfort, the current performance is regarded as acceptable since no request for improvement was made. However, the two retrofitting activities, install or upgrade insulation of external walls and roof, and change existing windows to low-e double glazing windows, which were proposed to achieve energy saving, may contribute to keeping or improving indoor thermal comfort with less use of HVAC.

Based on the above estimation, the environmental impacts of the proposed retrofitting activities are quantified and converted into numerical data. In the retrofitting stage, the environmental impacts caused by retrofitting construction are assessed, including embodied energy and embodied carbon emissions of building materials and service systems needed by proposed retrofitting activities, energy consumption and carbon emissions by operating construction equipment for implementing retrofitting activities, and the proportion of recyclable or reusable materials used in the proposed retrofitting activities. In the operation stage, the effects (improvement or decline compared to the performance before retrofitting) of the proposed retrofitting activities are assessed, including recurrent embodied energy and carbon emissions, difference (saving or additional amount by retrofitting activities) on energy consumption, carbon emissions, and water consumption by operating upgraded building service systems, proportion of recyclable or reusable materials and waste generation by replacing broken or obsolescent building materials or building service systems. As for indoor environmental quality, the pre-assessment was conducted to evaluate indoor thermal, visual and acoustic comfort to identify improvement areas for which potential retrofitting activities were proposed. It is not included in the decision making of retrofitting strategies in the following steps.

The assessment results that are used in later steps to develop retrofitting strategies, combining the assessment results of economic and social impacts, are summarised in Table 8.17, with all the assessment results rounded to whole numbers.

Table 8.17 Assessment results of environmental impacts by proposed retrofitting activities

Assessment criteria		**Unit**	**Retrofitting activities**									
			A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**
Retrofitting stage	Energy consumption	MJ	1,984,356	1,891,061	367,623	2,340	128,620	2,484	416,047	/	55,609	635
	Carbon emissions	kg CO_2	204,845	233,346	115,923	547	7,842	559	28,923	/	3,246	143
	Potential for reuse/recycling of materials	%	27	100	100	0	20	90	0	0	100	90
Operation stage	Potential savings on energy consumption	MJ	-39,834,588	-4,443,063	-6,219,638	-39,663,259	-15,535,300	-991,582	-3,273,980	-7,932,652	31,218	337,500
	Potential savings on carbon emissions	kg CO_2	-9,446,051	-1,383,976	-1,366,211	-8,924,234	-3,516,540	-223,106	-801,334	-1,784,847	2,012	75,938
	Potential savings on water consumption	kL	/	/	/	/	/	/	/	/	-61,688	-68,050
	Potential for reuse/recycling of materials	%	27	100	100	0	20	90	0	0	100	90
	Waste generation from replacement	kg	701,713	0	0	1,350	534	134	1,125	0	0	15

Note: The negative symbol "-" represents energy saving, carbon emissions reduction, or water consumption by retrofitting activities

A1. Install/upgrade insulation for external wall and roofs
A2. Change existing windows to low-e double glazing with aluminium frames
A3. Install aluminium sun shading slats for windows facing south
A4. Install motion sensors for lights
A5. Change T8 fluorescent bulbs to T8 LED
A6. Change existing lifts to energy efficient lifts
A7. Install PV panels
A8. Install building energy consumption monitoring system
A9. Change existing taps and toilets to water-saving ones
A10. Install water treatment system to recycle greywater and stormwater

8.2.4.2. Economic assessment – LCC method

The LCC method is used to calculate the equivalent annual cost (EAC) of the energy and water consumption after implementing the retrofitting activity. Based on Equation 4.3 (in Chapter 4), the initial costs in the retrofitting stage, and operation costs and replacement costs in the operation stage are converted to an equivalent annual value based on the current real discount in China. In this study, a current real discount rate of 8% is taken in the calculation, since it is often adopted for economic analysis in China in the current year, 2022 (Clark, Benoit & Walters 2022; Jin et al. 2022; Li 2022; Xu et al. 2022). The expected service life span of involved building components and service systems are adopted based on Australian Cost Management Manual – Volume 3 (Austalian Institute of Quantity Surveyors 2000), and studies by Kubba (2010), EATS (2015), Penny (2015), Kono et al. (2016), Alam et al. (2017), RICS (2018), and Tavares, Silva and de Brito (2020). The initial cost is estimated based on the relevant study and price provided by local suppliers of building materials and service systems. The sources are included in Appendix E-3. In addition, the electricity price for business use in China in 2022 is CNY 0.64/kWh, and the water price for business use in China in 2022 is CNY 0.49/kL according to CEIC database (CEIC 2022a; CEIC 2022b).

Based on the above assumption and information, the EACs of upgraded or newly added building service systems in a 50-year study period are calculated. The detailed calculation is in Table E3-1 in Appendix E-3. The calculation results are listed in Table 8.18.

Table 8.18. Assessment of economic performance

Upgraded building systems	**Retrofitting activity**		**Life expectancy**	**Retrofitting stage**	**Operation stage**								**EAC of the upgraded building service system after implementing the retrofitting activity**
				Initial cost	**Annual operation cost**	**Replacement cost (¥)**							
			years	**¥**	**¥**	**At year 15**	**At year 20**	**At year 25**	**At year 30**	**At year 35**	**At year 40**	**At year 45**	**¥**
HVAC	A1	External walls	20	771,376	103,411		771,376				771,376		155,673
		Roofs	20										
	A2		20	710,088	299,323		710,088				710,088		302,493
	A3		30	249,480	235,270				249,480				295,341
Lights	A4		15	70,200	329,058	70,200			70,200			70,200	337,356
	A5		30	83,810	414,403				83,810				421,935
Lifts	A6		30	2,625,390	8,226				2,625,390				244,160
PV panels	A7		30	34,900	-13,045				34,900				-9,908
BMCS	A8		15	270,000	-28,205	270,000			270,000			270,000	3,708
Water system	A9	Taps	50	11,000	2,734		47,300				47,300		7,113
		Toilets	20	47,300									
	A10		30	31,900	533				31,900				3,400

Note: The negative symbol "-" represents cost saving.

A1. Install/upgrade insulation for external wall and roofs
A2. Change existing windows to low-e double glazing with aluminium frames
A3. Install aluminium sun shading slats for windows facing south
A4. Install motion sensors for lights
A5. Change T8 fluorescent bulbs to T8 LED
A6. Change existing lifts to energy efficient lifts
A7. Install PV panels
A8. Install building energy consumption monitoring system
A9. Change existing taps and toilets to water-saving ones
A10. Install water treatment system to recycle greywater and stormwater

The EACs in Table 8.18 can only compare the cost saving ability of retrofitting activities when they contribute to electricity saving on the same building service system. For example, retrofitting activities A1, A2 and A3 can reduce electricity saving by HVAC. By implementing A1, A2 and A3, the EAC of HVAC will be CNY 155,675, CNY 302,493 and CNY 295,341, respectively. Therefore, A1 is the best one among them due to the least EAC achieved. However, the cost saving ability of A1, A4 and A6 cannot be directly compared based on Table 8.17, since they contribute electricity saving on different building service systems. In this study, the cost saving abilities of all the proposed retrofitting activities need to be assessed to compare their economic performance. Therefore, the cost and saving in the retrofitting stage and operation stage caused by each retrofitting activity are assessed, and they are converted as the annual equivalent cost or saving as Table 8.19 shows. The detailed calculation is in Table E3-2 in Appendix E-3.

Table 8.19. Equivalent annual cost or saving by retrofitting activities

Retrofitting activity		**Retrofitting stage**	**Operation stage**								**Equivalent annual cost or saving by retrofitting activities**
		Initial cost	**Potential savings on annual operation cost**	**Replacement cost (¥)**							
		¥	**¥**	**At year 15**	**At year 20**	**At year 25**	**At year 30**	**At year 35**	**At year 40**	**At year 45**	**¥**
A1	External walls	771,376	-155,127		771,376				771,376		-75,642
	Roofs										
A2		710,088	-29,216		710,088				710,088		43,954
A3		249,480	-23,269				249,480				-849
A4		70,200	-141,025	70,200			70,200			70,200	-132,728
A5		83,810	-55,680				83,810				-48,148
A6		2,625,390	-3,526				2,625,390				232,408
A7		34,900	-13,045				34,900				-9,908
A8		270,000	-28,205	270,000			270,000			270,000	3,708
A9	Taps	11,000	-605		47,300				47,300		5,169
	Toilets	47,300									
A10		31,900	533				31,900				3,400

Note: The negative symbol "-" represents cost saving.

A1. Install/upgrade insulation for external wall and roofs
A2. Change existing windows to low-e double glazing with aluminium frames
A3. Install aluminium sun shading slats for windows facing south
A4. Install motion sensors for lights
A5. Change T8 fluorescent bulbs to T8 LED
A6. Change existing lifts to energy efficient lifts
A7. Install PV panels
A8. Install building energy consumption monitoring system
A9. Change existing taps and toilets to water-saving ones
A10. Install water treatment system to recycle greywater and stormwater

Based on Table 8.19, retrofitting activity A4 – Install motion sensors for lights has the best economic performance among the proposed retrofitting activities, by creating the largest equivalent annual saving. Changing existing lifts to energy-efficient lifts (A6) has the worst economic performance due to the highest EAC. In addition, considering the retrofitting goal is to reduce at least 30% of operation cost (see Section 8.3.1), the savings on operation cost by each proposed retrofitting activity are calculated and illustrated in Table 8.20. The EAC or saving illustrated in Table 8.19 and saving percentage of operation cost in Table 8.20 are used to develop retrofitting strategies in later steps.

Table 8.20. Operation cost saving by retrofitting activities

Retrofitting activity		**Original operation cost (¥)**	**Potential savings on operation cost (¥)**	**Percentage of saving (%)**
A1	Install/upgrade insulation for external walls and roofs	1,186,953	155,127	13.07
A2	Change existing single-glazing windows to low-e double glazing with aluminium frames		29,216	2.46
A3	Install aluminium sun shading slats for windows facing south		23,269	1.96
A4	Install motion sensors		141,025	11.88
A5	Change T8 fluorescent bulbs to T8 LED		55,680	4.69
A6	Change existing lifts to energy efficient ones		3,526	0.30
A7	Install PV panels		13,045	1.10
A8	Install energy consumption monitoring system		28,205	2.38
A9	Change existing taps and toilets to water-saving ones		605	0.05
A10	Install water treatment system to recycle greywater and stormwater		-533	-0.04

8.2.4.3. Social assessment – rating score

Value score is adopted to quantify the social impacts of the proposed retrofitting activities. Five professionals of the focus group discussions, including one architect, two facility managers, and two engineers, were invited to assess the social impact of the retrofitting activities. They have all worked on the case building before. Based on their expertise in construction and property management and knowledge of the case building, they may give a proper social score for the proposed retrofitting activities. A questionnaire form was developed and sent to the five professionals by email. Based on the provided rating scale (see Section 6.7.1.2 and Table 6.4 in Chapter 6), they gave rating scores to the proposed retrofitting activities for each identified social criterion. It took about two weeks (17 to 31 August 2020) to collect all five completed questionnaires. The averages of the rating scores given by the five professionals are calculated based on Equation 6.1 in Chapter 6. The estimation results are listed in Table 8.21, and the detailed calculation is in Appendix E-4.

Table 8.21. Assessment of social impacts by retrofitting activities

Social assessment criteria		**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**
Retrofitting stage	Noise impact on neighbourhood	3.6	3.8	3.6	1	1	1	3	2	1	2.4
	Emission impact on neighbourhood	3.8	2.6	3.4	1	1	1	2.8	1.6	1	2.6
	Impacts on safety of undertaking the retrofitting activity	3.6	3.6	3.8	1.6	2.6	2.2	3.2	2	1.6	1.8
	Impacts on cultural heritage	3.8	3.8	4	1.4	1.6	2	3.8	2.4	2.6	3.6
	Impacts on surrounding traffic and pedestrians	4.2	3.4	3.4	1	1	1.4	2	2.2	1.2	2.4
	Impacts on relocating tenants	3.4	3.6	2.8	2.2	3.4	3.2	1.6	1.8	3.6	1.2
Operation stage	Accessibility to building facilities for people with additional needs	3.4	2.4	3.2	3.2	3	4.4	3.2	2.6	4.2	2.4
	Accessibility to building services (such as automatically adjusted indoor temperature and humidity by BMCS)	4.4	3.6	4.4	2.2	3.6	4	3.2	2.8	4.4	3.4
	Impacts on maintenance and maintainability from newly added building component or building system	3.4	2	2.6	2	3.6	3.6	2.2	3.4	3.6	2.4
	Impacts on safety and security of tenants	3.8	3.8	1.8	2	2.8	4.2	2.8	2.6	3.2	2.6
	Impacts on room flexibility for different demands	2.6	2.2	2.8	2	2.6	2.2	2	2.6	2.4	2.2

Note:

1. Rating score for assessing social performance of retrofitting activities

Impact range on retrofitting stage	**Score**	**Performance range in operation stage**
Minimum impact	5	Excellent performance
Minor impact	4	Very good performance
Average impact	3	Good performance
Significant impact	2	Same as current performance
Very significant impact	1	Unsatisfactory performance

2. Retrofitting activities
   A1. Install/upgrade insulation for external wall and roofs
   A2. Change existing windows to low-e double glazing with aluminium frames
   A3. Install aluminium sun shading slats for windows facing south
   A4. Install motion sensors for lights
   A5. Change T8 fluorescent bulbs to T8 LED
   A6. Change existing lifts to energy efficient lifts
   A7. Install PV panels
   A8. Install building energy consumption monitoring system
   A9. Change existing taps and toilets to water-saving ones
   A10. Install water treatment system to recycle greywater and stormwater

8.2.4.4. Determine weighted scores of retrofitting activities

To reach an aggregated overall score for the proposed retrofitting activities, the estimation in the environmental, economic and social dimensions is converted into unitless value by using the normalisation method, maximum/minimum ratio (Equations 6.5 and 6.6 in Chapter 6). This normalisation method compares the estimation results of all the proposed retrofitting activities in one assessment criterion. Then, the gap between one retrofitting activity and the best performed one can be measured. The gap is used to compare the performance range of all proposed retrofitting activities (the gap between the best and the worst). In this way, the estimation in different units can be converted to unitless. Moreover, the negative direction of measurement can be converted to positive in which the bigger normalised score will always present the better performance. The detailed process of normalising environmental, economic and social estimations can be found in Table E5-1 to Table E5-3 respectively in Appendix E-5.

Taking the environmental estimation in retrofitting stage as an example as Table 8.17 shows, retrofitting activity A8 has the best performance in energy consumption due to the least energy consumption (0 MJ), while retrofitting activity A1 has the worst performance with the most energy consumption (1,984,356 MJ). Therefore, the performance range of all the proposed retrofitting activities is 1,984,356 MJ. Since the measure direction is negative, the less energy consumption the better the performance. Therefore, Equation 6.6 (in Chapter 6) is used to normalise the estimation of energy consumption in the retrofitting stage of all proposed retrofitting activities. Two decimals are saved in normalisation results, and to have a clear and concise expression, the normalisation results are multiplied with 100 to make them integer. For example, the energy consumption in the retrofitting stage by retrofitting activity A3 is 367,623 MJ as shown in Table 8.22. Therefore, the normalised score of it can be calculated as:

$$
\begin{aligned}
a_{ij}^{*} &= \frac{max_{a_{ij}} - a_{ij}}{max_{a_{ij}} - min_{a_{ij}}} \times 100 \\
&= \frac{1984355 - 367623}{1984356 - 0} \times 100 \\
&= 81
\end{aligned}
$$

Table 8.22. Normalisation of environmental estimation in retrofitting stage

Assessment criteria Retrofitting activities		Energy consumption		Carbon emissions		Use of recyclable or reusable materials	
		Max=1,984,355 MJ; Min=0 MJ		Max=233,345 kg CO_2; Min=0 kg		Max=100%; Min=0%	
		Estimation (MJ)	Normalised score	Estimation (kg CO_2)	Normalised score	Estimation (%)	Normalised score
A1	Install/upgrade insulation for external walls and roofs	1,984,355	0	204,845	12	27	27
A2	Change existing single-glazing windows to low-e double glazing with aluminium frames	1,891,061	5	233,345	0	100	100
A3	Install aluminium sun shading slats for windows facing south	367,623	81	115,923	50	100	100
A4	Install motion sensors	2,430	100	547	100	0	0
A5	Change T8 fluorescent bulbs to T8 LED	128,620	94	7,842	97	20	20
A6	Change existing lifts to energy efficient ones	2,484	100	559	100	100	100
A7	Install PV panels	416,047	79	28,923	79	0	0
A8	Install energy consumption monitoring system	0	100	0	100	0	0
A9	Change existing taps and toilets to water-saving ones	55,609	97	3,246	97	100	100
A10	Install water treatment to recycle greywater and stormwater	635	100	143	100	90	90

The weights of the three sustainability dimensions and environmental and social assessment criteria for the operating model were determined at the focus group meeting (see Table 7.25 and Table 7.26 in Chapter 7). As for the economic dimension, the LCC method was employed to evaluate equivalent annual cost and saving by the retrofitting activities. In this method, the costs in different stages are regarded as equal. Therefore, their weights are equal to 1. By multiplying the normalised score with associated weights, the weighted scores of each proposed retrofitting activity in the environmental and social dimensions can be attained. Due to the equal importance of calculated costs, the weighted scores in the economic dimension are equal to normalised scores. By aggregating the weighted scores in one sustainability dimension, the total weighted score of the ten proposed retrofitting activities in the three sustainability dimensions can be achieved. The detailed calculation are in Table E5-4 in Appendix E-5, and the results are illustrated in Table 8.23.

Table 8.23. The total weighted scores in the three sustainability dimensions

Retrofitting activities		**Total weighted score after normalisation**		
		Environmental	**Economic**	**Social**
A1	Install/upgrade insulation for external walls and roofs	51.3	84.0	82.0
A2	Change existing single-glazing windows to low-e double glazing with aluminium frames	62.0	52.0	48.8
A3	Install aluminium sun shading slats for windows facing south	94.5	64.0	64.3
A4	Install motion sensors	101.3	100.0	106.5
A5	Change T8 fluorescent bulbs to T8 LED	85.1	77.0	134.1
A6	Change existing lifts to energy efficient ones	102.5	0.0	159.7
A7	Install PV panels	60.0	66.0	69.8
A8	Install energy consumption monitoring system	72.5	63.0	114.6
A9	Change existing taps and toilets to water-saving ones	116.3	62.0	157.2
A10	Install water treatment to recycle greywater and stormwater	114.1	63.0	86.1

8.2.5. Develop retrofitting strategies

A binary linear mathematical model (Equation 6.9 in Chapter 6) is established to develop retrofitting strategies. Three elements need to be specified to establish the mathematical model: retrofitting goals, project constraints, and weights of the three sustainability dimensions. As discussed in Section 8.2.1, two retrofitting goals are defined. One is a must-achieve goal: to achieve at least a 30% reduction of operation cost, and another is an expectation: to obtain a national green building label. Therefore, the Chinese national green retrofitting standard:

Assessment Standard for Green Retrofitting of Existing Buildings (GB/T 51141-2015) (MOHURD 2015) is used to assess the performance of the developed retrofitting strategies to check whether the developed retrofitting strategies can help the case building achieve the green building label. Meanwhile, the effectiveness of the decision model can further confirm if the green label can be achieved.

The project constraint is the proposed budget by the building owners of CNY 3 million. The weights of the three sustainability dimensions were developed in focus group meetings (see Table 7.26 in Chapter 7). By substituting these three figures into Equation 6.9 in Chapter 6, the binary linear mathematical model for developing retrofitting strategies for the case building can be established, as Equation 8.1 shows.

$$max\,Z = 0.437\sum_{j=1}^{10} P_j^{en}\,x_j + 0.324\sum_{j=1}^{10} P_j^{ec}\,x_j + 0.239\sum_{j=1}^{10} P_j^{s}\,x_j \qquad \text{Equation 8.1.}$$

$$s.t.\begin{cases} \sum\limits_{j=1} a_{1j}x_j \geq 30\% \\ \sum\limits_{j=1} a_{2j}x_j \leq 3{,}000{,}000 \\ x_j = 0{,}1 (j = 1{,}2{,}\ldots{,}10) \end{cases}$$

Where,

Z – the overall performance of a retrofitting strategy

P_j^{en} – the total weighted environmental score of retrofitting activity j, which can be found in Table 8.21

P_j^{ec} – the total weighted economic score of retrofitting activity j, which can be found in Table 8.21

P_j^{s} – the total weighted social score of retrofitting activity j, which can be found in Table 8.21

$\sum_{j=1} a_{1j}x_i \geq 30\%$ – the constraint function for satisfying the retrofitting goal, to achieve at least 30% saving of operation cost, and a_{1j} is the saved operation cost by each proposed retrofitting activity, which can be found in Table 8.20

$\sum_{j=1} a_{2j}x_i \leq 3{,}000{,}000$ – the constraint function for subjecting to the project constraint, CNY 3,000,000 project budget, and a_{2j} is the initial cost of each proposed retrofitting activity, which can be found in Table 8.18.

$x_j = 0{,}1$ – whether retrofitting activity x_j is selected. When $x_j = 0$, it is not selected. When $x_j = 1$, it is selected.

Excel is used to formulate Equation 8.1 as Table 8.24. By undertaking "SUMPRODUCT" formula and "SOLVER" order in Excel, the "optimal" retrofitting strategy can be developed, which can maximise overall improvement in environmental, economic and social dimensions within the CNY 3 million project budget, and reach the retrofitting goal, to achieve at least a 30% saving on operation cost. The selected retrofitting activities by running the program will be noted as "1" in the "select or not" column. The developed results by Excel using Solver are presented in Table 8.25.

Table 8.24. Establishing Equation 8.1 in Excel

Retrofitting activity (a_j)	**Environmental dimension (P_j^{en}) (weight=0.437)**	**Economic dimension (P_j^{ec}) (weight=0.324)**	**Social dimension (P_j^{s}) (weight=0.239)**	**% of operation cost saving by retrofitting activities (a_{1j})**	**Initial cost of retrofitting activities (a_{2j})**	**Select or not (x_j)**
A1	51.3	84.0	82.0	13.07%	771,376	
A2	62.0	52.0	48.8	2.46%	710,088	
A3	94.5	64.0	64.3	1.96%	249,480	
A4	101.3	100.0	106.5	11.88%	70,200	
A5	85.1	77.0	134.1	4.69%	83,810	
A6	102.5	0.0	159.7	0.30%	2,625,390	
A7	60.0	66.0	69.8	1.10%	34,900	
A8	72.5	63.0	114.6	2.38%	270,000	
A9	116.3	62.0	157.2	0.05%	58,300	
A10	114.1	63.0	86.1	-0.01%	31,900	
The overall weighted score of the developed retrofitting strategy (Z): $max\ Z = 0.437\sum_{j=1}^{10} P_j^{en}x_j + 0.324\sum_{j=1}^{10} P_j^{ec}x_j + 0.239\sum_{j=1}^{10} P_j^{s}x_j$						
Operation cost saving by the developed retrofitting strategy (%): $\sum_{j=1} a_{1j}x_j \geq 30\%$						
Total initial cost of the developed retrofitting strategy (¥): $\sum_{j=1} a_{2j}x_j \leq 3{,}000{,}000$						

Table 8.25. The developed retrofitting strategy for the case building

Retrofitting activity (a_j)	**Environmental dimension (P_j^{en}) (weight=0.437)**	**Economic dimension (P_j^{ec}) (weight=0.324)**	**Social dimension (P_j^{s}) (weight=0.239)**	**% of operation cost saving by retrofitting activities (a_{1j})**	**Initial cost of retrofitting activities (a_{2j})**	**Select or not (x_j)**
A1	51.3	84.0	82.0	13.07%	771,376	1
A2	62.0	52.0	48.8	2.46%	710,088	1
A3	94.5	64.0	64.3	1.96%	249,480	1
A4	101.3	100.0	106.5	11.88%	70,200	1
A5	85.1	77.0	134.1	4.69%	83,810	1
A6	102.5	0.0	159.7	0.30%	2,625,390	0
A7	60.0	66.0	69.8	1.10%	34,900	1
A8	72.5	63.0	114.6	2.38%	270,000	1
A9	116.3	62.0	157.2	0.05%	58,300	1
A10	114.1	63.0	86.1	-0.01%	31,900	1
The overall weighted score of the developed retrofitting strategy (Z): $max\ Z = 0.437 \sum_{j=1}^{10} P_j^{en} x_j + 0.324 \sum_{j=1}^{10} P_j^{ec} x_j + 0.239 \sum_{j=1}^{10} P_j^{s} x_j$				741.65		
Operation cost saving by the developed retrofitting strategy (%): $\sum_{j=1} a_{1j} x_j \geq 30\%$				37.58%		
Total initial cost of the developed retrofitting strategy (¥): $\sum_{j=1} a_{2j} x_j \leq 3{,}000{,}000$				2,280,054		

According to Table 8.25, nine out of the ten proposed retrofitting activities are selected to amalgamate the "optimal" retrofitting strategy, except retrofitting activity A6 (change existing lifts to energy efficient lifts). The developed retrofitting strategy (consists of retrofitting A1–A5 and A7–A10) can achieve about a 38% saving on operation cost with CNY 2,280,054 initial cost. The overall weighted score of the retrofitting strategy regarding environmental, economic and social dimensions is 741.65. Indeed, changing existing lifts to energy efficient ones can only achieve about 0.3% saving on operation cost with the highest initial cost among all proposed retrofitting activities.

Based on estimation of proposed retrofitting activities, the national green building label for retrofitting (GB/T 51141-2015) (MOHURD 2015) is used to check whether the case building can achieve a green building label by using the developed retrofitting strategy. In the standard, assessment is conducted in two stages. The first stage is the pre-assessment, which is conducted after the retrofitting design is finished. Five assessment categories are identified for the pre-assessment, planning and architecture, structure and materials, performance of HVAC, performance of water system, and electricity use. The second stage is to assess the performance of the building after retrofitting construction is finished. In addition to the above five categories, another two assessment categories are identified for this stage – construction management, and operation management. The pre-assessment is conducted in this case study to assess the performance of the developed retrofitting strategy.

Same as most of GBRS, the scores assigned in the standard (GB/T 51141-2015) (MOHURD 2015) are also unitless. GB/T 51141-2015 classifies the greenness or sustainability level into three grades – one star, two stars or three stars, based on the achieved overall score:

- 50 ≤ overall score < 60: ★
- 60 ≤ overall score < 80: ★★
- Overall score ≥ 80: ★★★

The national standard is a self-assessment system; by ticking off the items that have been met, the associated score assigned by the standard can be achieved. The overall score is the sum of the product of the achieved score in each category and the corresponding weight (given in the standard). By conducting the self-assessment based on this national standard (GB/T 51141-2015) (MOHURD 2015), the building can be labelled as a two-star building if using the developed retrofitting strategy. The assessment results are illustrated in Table 8.26.

Table 8.26. Assessment results based on the national green building standard

Assessment criteria	**Weight (given in the standard)**	**Achieved score**
Plan and architecture	0.21	73
Structure and materials	0.19	70
Performance of HVAC	0.27	60
Performance of water system	0.13	41
Electricity use	0.20	52
Overall score	60.56	
Grade of green building	★★	

8.2.6. Conduct sensitivity analysis

The sensitivity analysis is conducted to identify uncertainties that may affect decision results, and to check the scale of effects that may be caused by identified uncertainties. The OAT method is adopted to check whether uncertainties affect decision making results. In OAT, one parameter is changed at a time to check how much it may affect the decision-making result. In this case study, the discount rate, study period, and energy saving potential of proposed retrofitting activities are assumed based on existing studies, which may cause uncertainties. The discount rate may be more or less than the assumed one in the case study (8%). Therefore, ±5% based on the adopted discount rate (8%) is used to check how much effect may be caused by adopting different discount rates. A 50-year remaining service life is assumed in this case study, which is a common assumption in life cycle studies, and ± 20 years (30 years and 70 years) based on the adopted study period (50 years) is used to check how much effect may be caused by adopting different study periods. In addition, the potential energy savings by different retrofitting activities are adopted from existing studies, which may be sensitive to assessment results and decision making of retrofitting strategies. Based on Table E2-4 in Appendix E-2, retrofitting activities A1 (install/upgrade insulation for external walls and roofs) and A4 (change existing lifts to energy efficient lifts) have the largest potential for energy saving, which is about 12% for each. Therefore, ± 5% based on the adopted figures is used to check how much effect the adopted energy saving potential for retrofitting A1 and A4 may have.

Based on the above discussion, the sensitivity analysis is conducted by repeating the process from Section 8.2.4 to Section 8.2.5 with one parameter changed at a time. The analysis results are illustrated in Table 8.27, and changed parameters are summarised as below:

- Discount rate: 3% or 13%
- Study period: 30 years or 70 years
- Energy saving potential on HVAC by retrofitting activity A1: 55% or 65%
- Energy saving potential on lighting system by retrofitting activity A4: 25% or 35%

Table 8.27. Results of sensitivity analysis

Changed parameter		**Selected retrofitting activities**	**% of reduced annual operation cost**	**Total energy saving achieved in operation stage (MJ)**	**Equivalent annual saving by selected retrofitting activities (¥)**	**Overall weighted score (Z)**
Discount rate (i)	i=3%	A1–A5, A7–A10	37.58%	116,533,762	282,519	719.29
	i=13%		37.58%	116,533,762	120,497	757.53
Study period	30 years		37.58%	71,202,495	204,890	740.35
	70 years		37.58%	161,840,638	209,639	741.97
Energy saving potential of retrofitting activity A1 and A4	A1: 55% saving on HVAC system		36.37%	112,897,965	195,007	771.53
	A1: 65% saving on HVAC system		38.67%	120,169,561	224,417	748.08
	A4: 25% saving on lights		35.6%	109,923,219	187,986	753.25
	A4: 35% saving on lights		39.56%	123,144,306	234,994	727.46

Based on the results of the sensitivity analysis shown in Table 8.25, the changed parameters have no effect on the strategy development for the case study, in which A1, A2, A3, A4, A5, A7, A8, A9 and A10 are always selected and amalgamated as a retrofitting strategy in each analysis. However, they do have an effect on energy consumption and costs. Based on Table 8.25, the percentage of reduced annual operation cost by the developed retrofitting strategy does not change with a different discount rate or study period since these changes have equal impacts on operation cost. As for the changed energy saving potential of retrofitting activities A1 and A4, the bigger potential of them may contribute to more saving on annual operation cost, and the strength of impact by the change in retrofitting activity A4 is bigger than it is in retrofitting activity A1. In addition, the changes in Table 8.25 mainly impact the energy consumption in the operation stage. The longer study period is assumed, the more energy saving can be achieved in the operation stage. All the changes have an effect on the equivalent annual saving, and the change of discount rate has the biggest impact.

By changing these parameters, different overall weighted scores are achieved. It is noticed that the bigger energy saving potential of retrofitting activities A1 and A4 contributes to a smaller overall weighted score, which sounds wrong. In fact, it is correct. This situation is caused by the normalisation method, maximum/minimum ratio. In this normalisation method, by changing to a bigger energy saving potential, the performance range regarding energy saving ($(max_{a_{ij}} - min_{a_{ij}})$ in note 1 and 2) used to be 40,172,688 MJ (337,500 – (-39,834,588))

Note: 1. Equation 6.5 in Chapter6: $a_{ij}^{*} = \frac{a_{ij} - min_{a_{ij}}}{max_{a_{ij}} - min_{a_{ij}}}$ if assessed performance is positive impacts

2. Equation 6.5 in Chapter6: $a_{ij}^{*} = \frac{max_{a_{ij}} - a_{ij}}{max_{a_{ij}} - min_{a_{ij}}}$ if assessed performance is negative impacts

referring to Table A4-1 in Appendix A4. By changing the energy saving potential of retrofitting activity A1 from 60% to 65%, it achieves the largest energy saving compared to others. Accordingly, the performance range increases to 43,807,887 MJ (337,500 – (-43,479,387)). With the bigger denominator, even though the numerator remains unchanged (for other retrofitting activities), the normalised score will become smaller, resulting in a smaller overall weighted score. Therefore, the overall weighted scores can only be used to compare the overall sustainability performance of different amalgamations of a certain group of retrofitting activities. For example, there are ten retrofitting activities proposed for the case building. Among these ten retrofitting activities, the overall weighted score of retrofitting activities A1, A2 and A4 is bigger than of retrofitting activities A1, A2 and A6, representing that the overall sustainability performance of the retrofitting strategy consisting of A1, A2 and A4 is better than the one consisting of A1, A2 and A4. If another retrofitting activity was proposed other than these ten, the estimated overall weighted score for the 11 retrofitting activities cannot be used to compare with the scores when only ten activities are proposed.

Based on the above discussion, the changes of ±5% on the discount rate and energy saving potential of retrofitting activities A1 and A4, and ±20 years on the study period adopted in the case study do not affect decision-making results. In reality, the chance that these parameters change over these change ranges is small. Therefore, no further steps are needed to check how much effect they may have.

However, if results by the OAT method indicate that the decision results will be changed by changing selected parameters, it is necessary to check the effect on solutions that may be caused by these parameters. In this case, the range of changes need to be estimated first based on assumed probability distribution, such as a normal distribution. Then, based on the estimated range of changes, simulation tools for sensitivity analysis can be adopted to check the effects of these parameters, individually or jointly.

8.2.7. Determine the most preferred retrofitting strategy

The retrofitting strategy developed in Section 8.2.5 is the preferable solution regarding the identified retrofitting goal and the given project constraint. By relaxing or tightening the project constraint of the CNY 3 million project budget, four other options are developed for the building owners, as shown in Table 8.28.

Table 8.28. Alternative strategies by altering the project budget

Retrofitting strategies		**Selected retrofitting activities**	**Initial cost**		**% of reduced annual operation cost**	**Overall weighted score**	**Grade of green building**
			¥	**% of the original budget**			
1	The preferable strategy (the one developed in Section 8.3.6)	A1–A5, A7–A10	2,280,054	76%	37.58%	741.65	★★
2	Including all proposed retrofitting activities	A1–A10	4,905,444	164%	37.88%	818.59	★★
3	Reducing budget to 90% of the initial cost of Strategy 1	A1, A3–A5, A7–A10	1,569,966	52%	35.12%	681.16	★
4	Reducing budget to 60% of the initial cost of Strategy 1	A1, A4–A5, A7–A10	1,320,486	44%	33.16%	604.42	★
5	Reducing budget to 50% of the initial cost of Strategy 1	A1, A4–A5, A7, A9–A10	1,050,486	35%	30.78%	525.44	/

The preferable retrofitting strategy has included nine of the ten identified retrofitting activities. To amalgamate all the ten retrofitting activities as a retrofitting strategy (retrofitting strategy 2), the project budget has to increase by 64% (to CNY 4,905,444 as Table 2028 shows). Retrofitting strategy 2 may contribute to a 37.88% reduction in annual operation cost and attain the highest overall weighted score (818.59) among all alternatives and a two-star green building label.

The preferable retrofitting strategy developed in Section 8.3.6 has an initial cost of CNY 2,280,054, which is 24% below the budget. Therefore, by tightening the budget to 90% of the initial cost of retrofitting strategy 1, the retrofitting strategy (retrofitting strategy 3) amalgamated by retrofitting activities A1, A3, A4, A5, A7, A8, A9 and A10 is developed by running Equation 8.1 in Excel. Retrofitting strategy 3 can achieve a 35.12% operation cost saving with CNY 1,569,966 initial cost (69% of the initial cost of retrofitting strategy 1), and a one-star green building label, as shown in Table 8.28. By tightening the budget to 60% of the initial cost of retrofitting strategy 1, retrofitting strategy 4 amalgamating retrofitting activities A1, A4, A5 and A7–A10 is developed. It can achieve 33.16% of operation cost saving with

CNY 1,320,486 initial cost (58% of the initial cost of retrofitting strategy 1), and a one-star green building label. Finally, by tightening the budget to 50% of the initial cost of the "optimal" solution, alternative 5 can be developed, which contributes to 30.78% of operation cost saving with CNY 1,050,486 initial cost, and no green building label is achieved.

To conclude the results of retrofitting strategy development, there are five options for the building owners. Three options (retrofitting strategies 1, 3 and 4) can satisfy the retrofitting goals within the project budget with different levels of achievement. Retrofitting strategy 2 can best meet the retrofitting goals compared to others, but the initial cost may be over the budget by 64%. Retrofitting strategy 5 can meet the retrofitting goal for operation cost saving within the project budget, but no green building label can be achieved. Moreover, the sensitivity analysis indicates no significant effect on the decision-making results by changing the discount rate, study period or energy saving potential of retrofitting activities. With the given options, the building owners can make the final decision: spending the least money just to meet the retrofitting goals, spending more money to better meet the retrofitting goals, or spending more than half of the budget to "best" meet the retrofitting goals.

8.3. Outcomes and discussions

This chapter and the previous one conducted a case study to verify the validity of the conceptual model and illustrate the process of quantifying the conceptual model to develop retrofitting strategies for existing office buildings. In the case study, five retrofitting strategies are developed (see Table 8.28) regarding the identified retrofitting goals and project constraints, and the building owners can choose the preferred one to carry out. The validity and flexibility of the conceptual model, as well as the limitations, are discussed in the following sections.

8.3.1. Validity of the conceptual model

One purpose of the case study is to illustrate the validity of the conceptual model, by which a retrofitting strategy can be developed for the case building, which can maximise improvement in the environmental, economic and social dimensions within project constraints, and meet retrofitting goals at the same time.

The developed conceptual model can be adapted to suit office buildings in different climate zones. The case building is an office building in Hangzhou, Zhejiang, China. Therefore, it needs to be adapted to the Chinese retrofitting market before using it to develop retrofitting strategies for the case building. A two-stage data collection process from the broad to the specific was conducted in this case study to collect opinions from local professionals in the construction and property sector and key stakeholders, including building owners and tenants. Based on the collected opinions, the retrofitting activities and assessment criteria are revised to suit the situation of sustainable retrofitting in China, in which the conceptual model is converted to an operating model for Chinese retrofitting projects. By applying the operating model to develop retrofitting strategies for the case building, the retrofitting goals, problems of the case building, and suitable retrofitting activities are identified based on consultation with building owners, facility managers, and tenants, as well as investigation of the situation of the case building via a comprehensive audit. In addition, local data, such as applicable construction equipment for retrofitting construction, locally available building materials and service systems, and associated initial cost based on information provided by local suppliers, is used to measure the performance of the proposed retrofitting activities based on the finalised assessment criteria. In addition, the Chinese national standard for green retrofitting is used to confirm the effectiveness of the developed retrofitting strategies. Based on Table 8.26, the preferable retrofitting strategy, which maximises overall sustainability improvement within project constraints, can achieve two green stars. With a smaller overall weighted score achieved by retrofitting strategies 3 and 4, one green star can be achieved. The retrofitting strategy 5, having the lowest overall weighted score, cannot achieve a green building label.

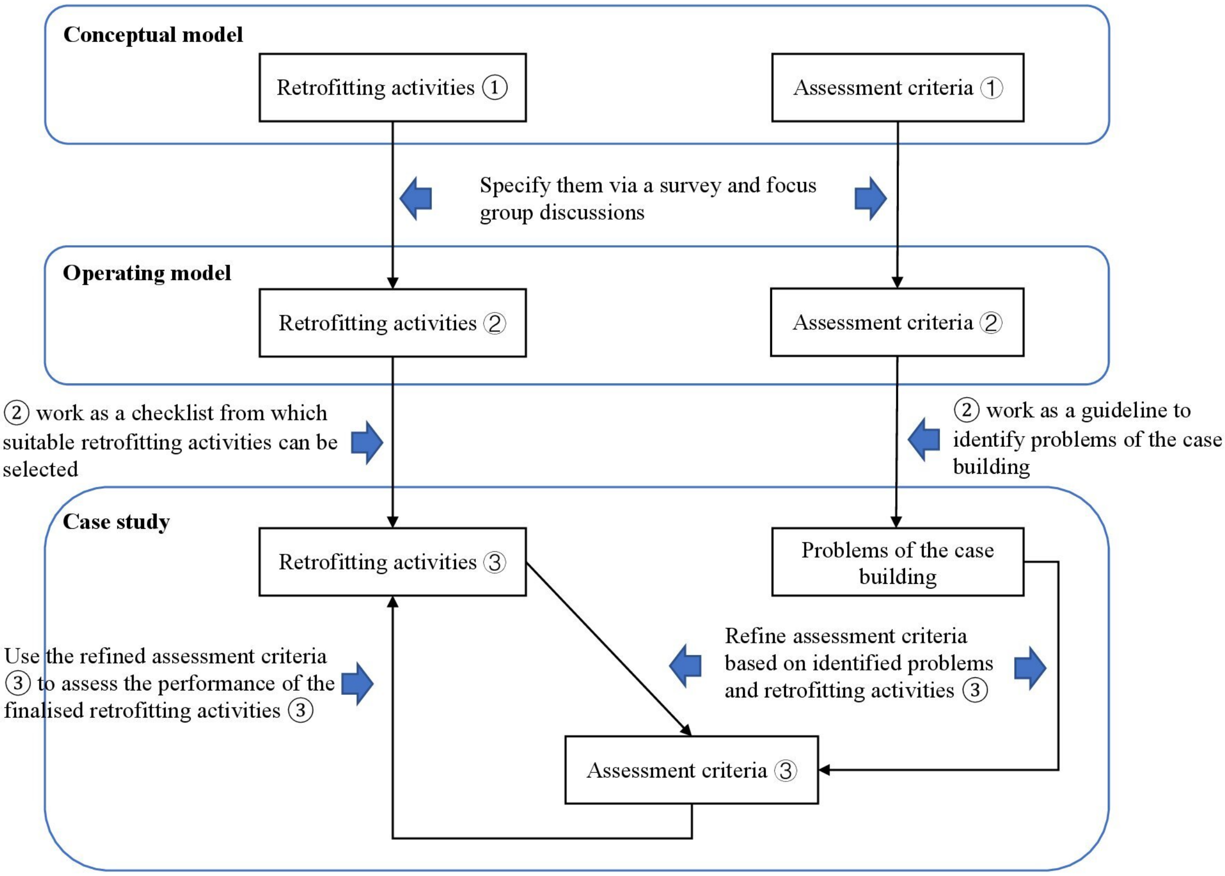
To conclude, the retrofitting strategies developed for the case building are based on opinions from local professionals and key stakeholders of retrofitting, deep investigation of the case building's problems, and proper estimation of the environmental, economic and social performance of the proposed retrofitting activities. The effectiveness of developed retrofitting strategies is also confirmed based on the Chinese national standard of sustainable retrofitting. Therefore, it can be stated that the case study illustrates the validity of the developed conceptual model. It provides a detailed illustration of using the conceptual model to develop retrofitting strategies for a real office building.

8.3.2. Applicability and flexibility of the conceptual model

China is a large country with different climate zones, resulting in different retrofitting demands. Therefore, it is a good opportunity to test the flexibility of the conceptual model. Due to historical energy scarcity and relevant heating standards, central heating is only available in the north for varying lengths of time. In the south, no district heating substations and long-distance heating pipelines have ever been provided. As a result of economic development over the past decades people who do not access central heating have begun to use air conditioners or heaters. For now, central heating is still available in the north, but mainly for residential buildings. For public buildings, especially office buildings, HVAC is becoming the main heat supply just as in the south. Based on the study by Li et al. (2018), apart from office buildings built before the 1980s, which were fitted with different cooling and heating facilities, such as fans and central heating supply, the newer office buildings built after that are air conditioned across the whole country. It means office buildings in China work in a similar way for cooling and heat supply. Consequently, the applicable retrofitting activities and suitable assessment criteria for measuring performance of retrofitting activities are similar in both regions. The difference of demands for retrofitting office buildings in the north and the south becomes small, such as different thickness of insulation materials needed in the two regions, which will not reduce the applicability of the operating model.

In addition, the iterative process of modifying retrofitting activities and assessment criteria to be suitable for use in China (illustrated in Figure 8.7) contributes to the increased flexibility of the operating model. In this case study, the assessment criteria and retrofitting activities are refined twice. To convert the conceptual model to an operating model, the retrofitting activities and assessment criteria are modified to suit the local situation based on a questionnaire survey and three focus group discussions. Based on the result of the survey, the identified retrofitting activities have been used by participants from both the north and the south, but with different proportions. It means all the provided retrofitting activities are applicable in northern and southern China. In addition, the added assessment criteria by the survey and focus groups, including impacts on surrounding traffic and pedestrians from retrofitting construction and the adaptability for different users, are actual impacts and expected performance from retrofitting activities, no matter where they are conducted. The added retrofitting activity, adding or upgrading insulation for the walls that subdivide the tenancy areas, is also suitable for both regions. Therefore, there is nothing to indicate the operating model is not applicable and flexible to be used for retrofitting strategies for office buildings in China.

Figure 8.7. An iterative process of information refining



In addition, the model is able to be adapted again based on the identified problems and specified retrofitting activities for the retrofitted building by removing irrelevant assessment criteria, adding new ones, and specifying required ones. For example, in this case study, due to the small amount expected, the waste generation in the retrofitting stage is not considered. According to the requirement by the local standard, the heat transfer coefficient of external walls should not be over 1 W/m^2•K. Due to the flexibility of the model, the actual situation of the retrofitting project can be considered, so that the developed retrofitting strategies can effectively improve the building's sustainability performance and meet the identified retrofitting goals.

However, two considerations about this case study need to be noted. First, the diversity of building materials and service systems cannot be considered in the developed model. For example, there are different insulation materials, which have different embodied energy, life span, insulation performance, initial costs etc. Different selection of insulation materials may result in different retrofitting strategies being developed. In principle, several different materials for each retrofitting activity can be included, but it may be time consuming, and even lead to an infinite decision-making process if the number of proposed retrofitting activities is large. Therefore, to develop suitable retrofitting strategies, it is important to consult with professionals who are able to identify retrofitting activities that have desirable traits and reasonable costs, and available construction technologies to implement them. In addition, there is a lack of post-occupancy evaluation, which can be used to obtain feedback on the effect of the developed retrofitting strategy and also to test the accuracy of estimation. A post-occupancy evaluation may need data on operating the building for at least one year after retrofitting, which cannot be finished in the study period of the thesis study. A post survey may be conducted as a follow-up study after the thesis study.

8.4. Summary

In summary, this chapter gave a detailed description of a case study, which demonstrates the process of using the operating model to develop retrofitting strategies for an office building in China. In the case study, five retrofitting strategies are developed with different levels of achieving retrofitting goals and costs. Combined with the discussion in Chapters 6 and 7, these three chapters present how the research question is answered: how can we develop a retrofitting strategy that can effectively improve a building's environmental, economic and social performance in a balanced way? With developed retrofitting strategies for the case building, the research proposition was justified, which it is possible to improve sustainability – which could be sufficient to allow economic growth and improved social wellbeing – by retrofitting existing buildings; and that this can be done by using the triple-bottom line approach. In the next chapter, the whole study is discussed and the thesis concluded.

Chapter 9. Summary and conclusions

9.1. Introduction

This chapter presents a summary of the study. It encapsulates the findings from the literature review, the development of a conceptual model for deciding retrofitting strategies for office buildings, and a case study that verifies the conceptual model and illustrates the process of implementing the model. The conclusions in this chapter link and integrate the research findings with the research aims and objectives. Meanwhile, based on the contribution and limitation of this study, suggestions for future research are also provided.

This thesis critically examines the current performance of existing office buildings in the environmental, economic and social dimensions, investigates common retrofitting activities for improving existing office buildings' performance in these three dimensions, and reviews existing assessment methods and decision-making frameworks of sustainability.

In acknowledging the substantial negative environmental, economic and social impacts from existing office buildings, and the effectiveness of sustainable retrofitting, this study develops a conceptual model for deciding retrofitting strategies for office buildings based on a comprehensive literature review. Then, it converts the conceptual model to an operating model to suit the local situation of a sustainable retrofitting based on a survey and three focus group discussions. In the end, the operating model is implemented to develop retrofitting strategies for the case building. The results show that it is possible to improve sustainability while potentially allowing economic growth and improved social wellbeing by retrofitting existing buildings using the triple-bottom line approach.

Based on the research process and achieved outcomes, this chapter discusses and summarises the study by providing an overview of research aims and objectives (Section 9.2), a summary of the whole research (Section 9.3), summary of contribution to knowledge (Section 9.4), discussion of the study limitations (Section 9.5), and recommendation for future studies (Section 9.6).

9.2. Overview of aims and objectives

This study has satisfied the research aim which is to develop a model for developing retrofitting strategies for office buildings to improve their sustainability performance (see Chapter 1). This model is able to develop retrofitting strategies for existing office buildings based on estimation of impacts of potential retrofitting activities in the environmental, economic and social dimensions. In addition, the long-term perspective is taken in the model which considers impacts of retrofitting activities in the retrofitting stage and operation stage. Ultimately, the model can help improve performance of existing buildings by covering all the sustainability dimensions from a long-term perspective. This study has satisfied several objectives to realise the research aim, as summarised below.

9.2.1. Current performance of existing office buildings in triple-bottom line aspects

The first objective is to examine the current performance of existing office buildings in the environmental, economic and social dimensions. The literature review in Chapters 2 and 3 confirmed the significance of sustainable development and the necessity of sustainable retrofitting to reduce negative impacts from the building sector. The literature revealed that the construction sector is consuming many resources and generating pollution of the natural environment, and it is a crucial field for realising sustainable development for the whole of society. To achieve overall sustainable construction, the impacts of construction activities in the triple-bottom line aspects – the environmental, economic and social dimensions – need to be considered.

The literature shows that most existing office buildings have poorer environmental sustainability performance than new buildings because of the stricter newer regulations about buildings' environmental impacts and increasing demands for indoor environmental quality. Due to the poor energy efficiency and outdated building materials and service systems, existing office buildings have higher operation and maintenance costs. On the social dimension, aging office buildings may lead to poor indoor comfort and less job satisfaction for building occupants. Considering the large quantity of existing buildings, their long service life, and the identified massive negative impacts, retrofitting is recognised as being a better remedy than demolition and new construction. Sustainable retrofitting can quickly improve existing buildings' environmental, economic and social performance, and can also retain the embodied energy and embodied carbon emissions in existing buildings and avoid more of them being created by new construction. There is a clear call for the construction and property management sector to adopt sustainable retrofitting to reduce their negative impacts on the environmental, economic and social dimensions.

9.2.2. Existing assessment methods for building retrofitting

The second research objective is to review literature about assessment methods for sustainable buildings and suggest ways to realise comprehensive assessment for sustainability and to aid developing sustainability strategies. In Chapter 4, the common assessment methods for evaluating sustainability performance of constructions were examined with the analysis of their benefits and limits. The literature reveals that most existing assessment methods fail to embrace all the three sustainability dimensions by focusing on one or combining the environmental and economic dimensions with the absence of the social dimension. Therefore, the assessment results of them cannot provide a complete picture of the sustainability performance of potential sustainability strategies.

The literature identifies two methods that can include all the three sustainability dimensions in assessment and the decision-making process: life cycle sustainability assessment and multi-criteria decision making. In life cycle sustainability assessment, the three sustainability dimensions are assessed based on the same methodology of life cycle assessment, but the mutual relations between the three dimensions are neglected in this method. In multi-criteria decision making, appropriate assessment methods in the three dimensions can be integrated and trade-offs between different assessment criteria can be analysed and balanced. Therefore, it is adopted in this study to build the conceptual model for deciding on retrofitting strategies.

The literature has revealed that existing sustainability assessments are insufficient to include all the three sustainability dimensions and analyse trade-offs between them. There is a need for a multi-dimensional framework that can provide a comprehensive assessment of sustainability and be an aid to decision making.

9.2.3. Identifying assessment criteria for sustainable retrofitting

The third and fourth research objectives are to identify suitable assessment criteria and trade-offs between the three sustainability dimensions, which need to be considered for retrofitting projects. Chapter 4 reviewed existing assessment methods of sustainability. Most methods are for new buildings, and there is a lack of an assessment method for sustainable retrofitting which can include all the three sustainability dimensions. In Chapter 3, the potential improvements by sustainable retrofitting are identified, and common retrofitting activities for office buildings are discussed. Based on information derived from the literature review, the desired attributes of sustainable retrofitting and existing office buildings in the three sustainability dimensions are identified and associated assessment criteria from relevant studies are selected in Chapter 6 as assessment criteria in the developed model.

Chapter 6 reviewed the general retrofitting process and showed that retrofitting is a complicated process with the involvement of different stakeholders at different life stages of the retrofitting building. Identifying trade-offs between different sustainability dimensions from a long-term perspective is key to weighing up the perspectives of different stakeholders. Chapter 6 defined the measurement of point-to-point trade-offs between assessment criteria. Since the three sustainability dimensions are considered for sustainable retrofitting in the developed model, the derivative of the point-to-point measurement by considering trade-offs between the three sustainability dimensions is investigated and represented in Appendix A.

In the literature, there is a clear call for a comprehensive model for sustainable retrofitting that can provide specified assessment criteria for each sustainability dimension and consider trade-offs between them by which suitable retrofitting strategies can be developed.

9.2.4. Developing a conceptual model for deciding retrofitting strategies for office buildings

The fifth research objective is to develop a conceptual model for developing retrofitting strategies for office buildings using the triple-bottom line approach. The literature review in Chapters 2 to 4 recognised that humans contribute to climate change. Based on the theory and information derived from the literature review, a research proposition was proposed in this study: it is possible to improve sustainability while potentially allowing economic growth and improved social wellbeing by retrofitting existing buildings using the triple-bottom line approach. This research proposition was justified based on a process from conceptualisation to operationalisation. The conceptualisation is realised by developing a conceptual model for developing retrofitting strategies for office buildings, which has been developed and illustrated in Chapter 6.

In the conceptual model, eight steps are identified for deciding retrofitting strategies: Step 1 – Set retrofitting goals and objectives; Step 2 – Identify problems; Step 3 – Propose retrofitting activities; Step 4 – Develop assessment criteria; Step 5 – Evaluate performance of retrofitting activities; Step 6 – Develop retrofitting strategies; Step 7 – Conduct sensitivity analysis; and Step 8 – Choose the "best" retrofitting strategy. In Step 3, the common retrofitting activities for retrofitting office buildings are identified, which can be used as a checklist for selecting suitable retrofitting activities for proposed projects. In Step 4, suitable environmental, economic and social assessment criteria for assessing the performance of existing buildings are summarised based on the literature review. They need to be modified to suit the local situation of sustainable retrofitting before using the model to develop retrofitting strategies for an office building. In Step 6, a binary linear mathematical model is established in which a preferable retrofitting strategy can be developed based on the resulting assessment outcomes of proposed retrofitting activities. The developed retrofitting strategy can maximise the overall improvement of the existing building in environmental, economic and social dimensions within project constraints, while meeting retrofitting goals.

9.2.5. Verifying the conceptual model and illustrating the implementation of the model

The last research objective is to verify the conceptual model and illustrate how to use the model to develop retrofitting strategies for an office building. To satisfy this research objective, a case study was conducted in Hangzhou, China. Since the conceptual model intends to be general, it needs to be adapted to suit the specific situation of sustainable retrofitting in China. In Chapter 7, the conceptual model was converted to an operating model (operationalisation) for use in China by revising the retrofitting activities and assessment criteria. China is the world's largest construction market, but the performance of existing buildings does not meet the requirements of sustainable buildings. The large number of buildings built in the past 30 years are now due for retrofit.

In China, the difference between buildings in the north and the south is mainly the different methods of heat supply. In the north, there is central heat supply available for varying lengths of time, but HVAC or heaters are the only heat supply in the south. However, the difference exists mainly in residential buildings in the north and the south. As a result of economic development over the past decades in China, office buildings built after the 1980s are air conditioned across the whole country. HVAC has become the major intervention for indoor thermal comfort for office buildings in China by providing heating in winter and cooling in summer. Therefore, even though China is a big country with various climate conditions, the office buildings across the country have a similar way of operating, and it provides a good opportunity to test the flexibility of the developed model.

To convert the conceptual model to an operating model for use in China, opinions about suitable retrofitting activities and assessment criteria for sustainable retrofitting in China were collected from professionals in the construction and property management sector and key stakeholders of retrofitting. A two-stage strategy was adopted to collect data from the broad to the specific. First, a survey was conducted in the north and the south to collect broad and general opinions. Then, three discussion groups were organised to confirm the results of the survey, and to further modify the retrofitting activities and assessment criteria to be suitable for use in China. At the end of focus group discussions, participants were invited to decide weights for the three sustainability dimensions and the assessment criteria under them using the Analytic Hierarchy Process. In this way, the conceptual model was converted to an operating model that can be used to develop retrofitting strategies for office buildings in China.

In Chapter 8, the operating model was used to develop retrofitting strategies for the case building. By following the steps in the conceptual model, ten potential retrofitting activities that may solve the problems of the building were proposed. Based on the evaluation of environmental, economic and social impacts on the retrofitting stage and operation stage, the preferable retrofitting strategy that can maximise the overall improvement on the three sustainability dimensions while meeting retrofitting goals was developed by running the binary linear mathematical model in Excel. By relaxing or tightening the project constraints, four other retrofitting strategies were developed. The building owner can simply choose the strategy that can best meet their demands as the final retrofitting strategy. To verify the effectiveness of the conceptual model, the Chinese national standard of green retrofit is used to assess whether the national green building label can be achieved by implementing the developed retrofitting strategies. The result shows that the building can achieve two green stars if the preferable retrofitting strategy is implemented. Based on the developed retrofitting strategies for the case building, and the verified effectiveness of the conceptual model, Chapter 8 illustrated the validity of the conceptual model and provided a detailed process for using the conceptual model to develop retrofitting strategies for an office building.

9.2.6. Conclusion

In conclusion, this study has achieved the research aim and objectives by developing a model that can be used to develop retrofitting strategies for office buildings by integrating the environmental, economic and social dimensions. In addition, the developed model has been tested and verified based on a case study, indicating that by implementing the retrofitting strategies developed by the model, the sustainability performance of existing office buildings can be effectively improved.

9.3. Summary of the research

This research aimed to develop a model for deciding retrofitting strategies for office buildings to improve their sustainability performance. It firstly investigated the significance of sustainable development of construction by emphasising the necessity and challenges facing sustainable construction. Based on the literature review, the necessity of sustainable construction was confirmed, and four points were identified which are crucial to overcome those challenges:

- Environmental, economic and social dimensions should be integrated and balanced in an optimal manner.
- A long-term perspective should be adopted for investigating impacts on the three sustainability dimensions.

- The assessment method and assessment indicators should be thoroughly studied and determined for each sustainability dimension.
- A universal unit should be adopted for comparison and decision making.

To achieve genuine sustainable retrofitting, these four points are considered and carefully integrated in the developed model.

By investigating the current performance of existing office buildings around the world, it was shown that most existing office buildings have poor performance on environmental, economic and social dimensions, not only because of aging building materials and service systems, but also increasing demands for indoor environmental quality. With the large quantity of existing buildings in the world, the rate of new buildings added to the whole building sector is only around 1% a year. Therefore, compared to demolition and then building new buildings, retrofitting existing buildings can deliver a faster improvement on sustainability performance of the whole building sector. Moreover, by largely reusing existing structure and materials, retrofitting can save embodied energy and embodied carbon emissions embedded in existing buildings. Therefore, sustainable retrofitting is regarded as an effective way to improve the sustainability performance of existing buildings. Ultimately, the overall sustainability performance of the whole building sector may be improved.

Based on existing studies about building retrofitting, 15 common retrofitting activities for office buildings were identified with the emphasis on potential improvement on the three sustainability dimensions. In addition, the level of interruption to existing tenants by implementing these retrofitting activities was discussed and categorised. Based on the potential contribution and different level of interruption to existing tenants, the identified retrofitting activities were categorised, which may help select suitable retrofitting activities.

Suitable retrofitting strategies cannot be developed if the performance of proposed retrofitting activities is not assessed appropriately and comprehensively. This study reviewed common assessment methods in each sustainability dimension. Life cycle impact and green building rating systems are two common methods to assess environmental impact. For the economic dimension, life cycle costing and cost benefit analysis are widely used to evaluate income and costs throughout a product's life cycle. Social cost benefit analysis and social life cycle impacts are two methods that can be adopted to assess social impact. Often environmental and economic assessments are integrated as a two-pillar model for assessing the sustainability performance of construction. As an indispensable component of sustainability, the social dimension conveys both the tangible and intangible benefits of sustainability. Therefore, it is desirable for assessment models or frameworks to integrate all the sustainability dimensions and generate an overall assessment result to aid in decision making.

Life cycle sustainability assessment is a three-pillar model built on the principle of the triple-bottom line. In life cycle sustainability assessment, environmental impact is assessed using environmental life cycle assessment, the economic dimension is assessed using environmental life cycle costing, and social life cycle assessment is used to assess social impacts. These three techniques have the same methodology based on the standard ISO 14040 (ISO 2006a). Life cycle sustainability assessment is praised for providing a whole picture for sustainability assessment by including all the three sustainability dimensions. However, it models each pillar of sustainability independently; thus, the assessment results in each pillar do not facilitate the decision-making process unless they are amalgamated into a decision-making support system.

Deciding retrofitting strategies is a complex process that needs careful assessment in different sustainability dimensions, clear understanding and managing trade-offs between different assessment criteria, and the ability to deal with competing retrofitting objectives. Multi-criteria decision making is believed to be able to fulfill these requirements. Multi-objective decision making and multi-attribute decision making are two branches of multi-criteria decision making. Multi-objective decision making can generate optimal solutions within project constraints, while multi-attribute decision making is usually used to select the "best" solution from a pool of predetermined alternatives. Due to the nature of retrofitting projects, the possibilities for the site should be compared to one another rather than to strict goals. The optimisation model is more suitable for generating retrofitting strategies since it can provide the best overall and balanced performance regarding the three sustainability pillars. Therefore, multi-objective decision making was adopted in this study to build the conceptual model for deciding on retrofitting strategies.

Based on the information derived from the literature review, a conceptual model for deciding retrofitting strategies for office buildings was developed. In the conceptual model, the environmental, economic and social impacts of potential retrofitting activities are assessed, and the assessment outcomes are normalised to unitless values, so they can be aggregated as one to support decision making. By using the conceptual model, the developed retrofitting strategy is able to maximise the overall improvement in the environmental, economic and social dimensions within project constraints, while meeting retrofitting objectives. Following the model development, a case study was conducted to verify the validity of the conceptual model and illustrate the detailed process of using the conceptual model to develop retrofitting strategies for an office building, as discussed in Section 9.3.5.

9.4. Contribution to knowledge

The main contribution of this research is to develop a model for deciding retrofitting strategies for office buildings. With the development and verification of the model, this research successfully addresses the research gaps identified in Chapter 1:

- The developed model is able to deal with environmental, economic and social issues of existing office buildings, and provide appropriate assessment of impacts of potential retrofitting activities in the three sustainability dimensions.
- The developed model provides a comprehensive framework of sustainable retrofitting from assessing impacts of retrofitting activities in the three sustainability dimensions to using the resulting assessment outcomes to develop suitable retrofitting strategies.
- The developed model is able to analyse trade-offs between different assessment criteria and sustainability dimensions from a long-term perspective. Therefore, the developed retrofitting strategies may maximise benefits among different stakeholders, contributing to effective promotion of sustainable retrofitting.

The developed model consists of two parts – the conceptual and the operational. The conceptual model is developed based on the literature review. It outlines general steps for developing retrofitting strategies, and provides common retrofitting activities and assessment criteria for sustainable retrofitting for office buildings. By modifying retrofitting activities and assessment criteria, the conceptual model can be adapted to an operating model to suit the specific situation of sustainable retrofitting in any location with any climate condition.

In this research, a case study was conducted to illustrate the process of the conceptualisation to operationalisation. First, a survey and three focus group discussions were conducted with local professionals in the construction and property management sector and key stakeholders to modify retrofitting activities and assessment criteria to be locally suitable, which enabled the conceptual model to be converted to an operating model. The operating model was then used to develop retrofitting strategies for the case building. The conceptual model considers all the various strategies for retrofitting, and the operating model is a quantified set for a specific location or region. The whole process can test whether the research proposition is correct or not. Then the process from converting the conceptual model to an operating model to quantifying the operating model using a case study can be recognised as a logically and methodologically correct framework for the work done and to be done in the future. By copying the process, the conceptual model can be adapted according to the specific situation of each retrofitting project and used to develop retrofitting strategies.

9.5. Limitations of this research

The research carried out in this thesis is significant and the developed model can be adapted and used to develop retrofitting strategies for office buildings. However, there are some limits of this research which need to be recognised.

First, the diversity of building materials and service systems cannot be considered in the developed model. However, different materials have different embodied energy, life span, insulation performance, and initial costs that may result in different retrofitting strategies being developed. The model assumes that the determined type and composition of building materials and service systems in each retrofitting activity is the optimum for the retrofitted building. In the case study, the suitable and locally available building materials and service systems for the proposed retrofitting activities were determined based on consultation with local professionals in the construction and property management sector. Without considering impacts of different types and composition of building materials and service systems, even though the developed retrofitting strategies can meet identified retrofitting goals within the given project constraints, the model cannot ensure that it is the optimal solution for meeting the retrofitting goals under the given project constraints.

Second, there is a lack of post-occupancy evaluation in the case study, which could be used to obtain feedback on the effect of the developed retrofitting strategy, especially on the indoor environmental quality. In the case study, only a pre-assessment of indoor environmental quality was conducted to identify improvement areas for which potential retrofitting activities could be proposed. Therefore, a post evaluation is necessary to understand how the retrofitting strategy developed by the model improves indoor environmental quality. A post evaluation could also test the accuracy of estimation. The results of a post survey could be used to calibrate the assessment and decision-making process in the developed model. However, for a post evaluation, data is needed on operating the building for at least one year after retrofitting, which cannot be achieved within the thesis study period. A post-occupancy evaluation may be conducted as a follow-up study after the thesis study.

Thirdly, demands of commercial office buildings may differ to some extent after the COVID-19 pandemic. Since the emergence of COVID-19 in late 2019, the format of people's daily life and work has changed. The decrease in social activities and a new form of work, working from home, make it uncertain what the demands for office buildings may be in the future. Meanwhile, likely future pandemics also lead to uncertainty about demand for offices, even new construction. In this study, the conceptual model was developed, and the survey and focus group discussion were conducted before the emergence of COVID; thus, the impact of the COVID pandemic on demands for office buildings could not be reflected in this study. However, when applying this model to develop retrofitting strategies, infectious disease pandemics need to be considered, especially in the steps to identify retrofitting activities and develop assessment criteria.

9.6. Recommendations for future research

As indicated above, this research has developed a model for deciding retrofitting strategies for office buildings to improve their sustainability performance. During the research, it was noted that there is scope for future study. The following research is desirable to extend and modify the findings in this study.

9.6.1. Develop a decision model to select suitable building materials for retrofitting

As discussed in Section 9.5, the developed model does not consider the diversity of building materials, which may have significant impacts on the insulation performance of external walls, roofs and windows. In fact, the model can be adapted to a decision model to select suitable building materials for retrofitting. By focusing on building materials, the assessment criteria need to be adapted to suit the context of impacts of building materials instead of retrofitting activities. There are multiple studies about evaluating the environmental and economic performance of building materials. Similar to most studies about sustainable construction, the social dimension does not get sufficient attention. The definition and assessment of the social performance of different building materials is relatively vague. Therefore, more efforts are needed to identify social assessment criteria for selecting suitable building materials.

Once the assessment criteria for the three sustainability dimensions are identified, the binary linear mathematical model in the conceptual model can be adapted to select suitable building materials for retrofitting, such as revising the objective function according to the expected U-value of insulation materials. The expected outcomes are that several building materials can be identified to meet different decision rules, such as the best insulation performance, the most cost effectiveness, or the best overall sustainability performance. In this way, a limited, manageable number of types of building materials can be identified. However, the selection of building materials is sensitive to the climate condition. Therefore, the model should be adapted to select suitable retrofitting materials for regions with different climate conditions.

9.6.2. Include a post-occupancy evaluation in the model

Due to the time constraint, post-occupancy evaluation is not included in this study. However, the feedback obtained by a post-occupancy evaluation could help verify the effectiveness of the developed model. The results of a post-occupancy evaluation could test the accuracy of assessment and be used to calibrate the assessment and decision-making process in the developed model, especially when the converted operating model is used for a region instead of a single building. By improving the operating model based on the results of post-occupancy evaluation in previous retrofitting projects in the same region, great improvement in the accuracy and effectiveness of the developed model is likely.

9.6.3. Adapt the model to be used for the public sector

The model developed in this study only considers the internal factors which are directly relevant to individuals, such as building owners, tenants, facility managers, and people visiting the buildings. However, the external factors that are relevant to the whole community or society, such as how the retrofitted building fits into the streetscape, and whether sustainable retrofitting can contribute to less public investment in energy production, are not considered. External factors of sustainable retrofitting are normally considered by governments to plan the development of communities or the whole of society. Therefore, it is worth adapting the model by incorporating external factors to develop retrofitting strategies. Moreover, with the support of government, it is more possible to convert the conceptual model to operating models for different regions in a country and use them as a guideline for retrofitting office buildings. In this way, the overall sustainability performance of existing buildings may be improved effectively in line with the direction of the government's macro planning.

9.6.4. Extend the model

This study has concentrated on investigating ways to improve the sustainability performance of existing office buildings by sustainable retrofitting. The outcome is a conceptual model and an illustration of converting the conceptual model to an operating model to develop retrofitting strategies for an office building in China. The outcome provides many opportunities for future research.

First, the literature review on sustainable retrofitting reveals there are many studies about the environmental and economic performance of office buildings, but limited study about the social performance of office buildings. In this study, only the social impacts of implementing retrofitting activities and operating retrofitted office buildings are considered. In fact, there are other social impacts caused by retrofitting activities, such as corporate governance and productivity of workers in the building. However, as discussed in Chapter 3, the split benefit, in which tenants receive the benefits of retrofitting paid for by building owners, is a barrier to sustainable retrofitting. Therefore, the building owners are less likely to care whether retrofitting can contribute to improved corporate social responsibility and productivity. However, it is different if the building owners occupy the office building. In this case, the improved social performance may become the driver of sustainable retrofitting. Therefore, future research could either investigate more comprehensive sustainable retrofitting by identifying and incorporating other applicable social impact assessment criteria, or analysing retrofitting outcomes from different perspectives, such as adapting the model to develop retrofitting strategies for office buildings that are occupied by owners,

Second, this research only investigated sustainable retrofitting for office buildings. There is huge potential for sustainability improvement in other building types, such as residential buildings, school buildings, hospitals, shopping malls, and retail stores. Therefore, future studies can investigate each type of building to identify possible retrofitting activities and suitable assessment criteria in the three sustainability dimensions. By doing this, the rate of enhancing sustainability performance of the whole building sector can be accelerated.

Third, this research only considered buildings themself, and the outdoor landscape was not included. In future research, the outdoor landscape of buildings can be included to maximise the effect of sustainable retrofitting. In this case, the retrofitting activities that can improve outdoor environment, such as planting more greenery around the building and adding access to the building, should be considered. Accordingly, the related environmental and social assessment criteria, such as the increased rate of outdoor greenery and improved accessibility to the building should also be considered and evaluated.

Fourth, the case study in this research only investigated retrofitting activities and assessment criteria of sustainable retrofitting of office buildings in China. Climate change is a global crisis. The existing buildings across the world have negative impacts on the natural environment. It is necessary to conduct sustainable retrofitting for office buildings throughout the world. International application of the developed model will provide interesting opportunities for comparisons and information exchange. These opportunities will strengthen the methodology for practising sustainable retrofitting of office buildings, thereby reducing the environmental impact of existing office buildings.

9.7. Conclusion

This research aims to develop a model for deciding retrofitting strategies for office buildings to improve their sustainability performance. A series of research objectives were identified and met to realise this research aim, including an extensive review on sustainable construction, current sustainability performance of existing office buildings, common retrofitting activities for office buildings, applicable assessment criteria for sustainable retrofitting of office buildings, and common assessment methods of sustainability performance; development of a conceptual model for deciding retrofitting strategies for office buildings; and a case study for verifying the conceptual model and illustrating the process of implementation of the model.

The research outcomes indicate that the model is able to develop retrofitting strategies that can maximise the overall sustainability performance of an existing building in the environmental, economic and social dimensions within project constraints, while meeting retrofitting goals. Moreover, the conceptual model is flexible and can be adapted to suit the local situation of sustainable retrofitting, in a way that locally suitable and applicable retrofitting strategies can be developed. The process from conceptualisation to operationalisation in the research provides a logically and methodologically correct framework for the work done and to be done in the future. By retrofitting existing office buildings using the retrofitting strategies developed by the model, the sustainability performance of the whole building sector is expected to improve effectively.

Appendices

Appendix A. Trade-off between three attributes

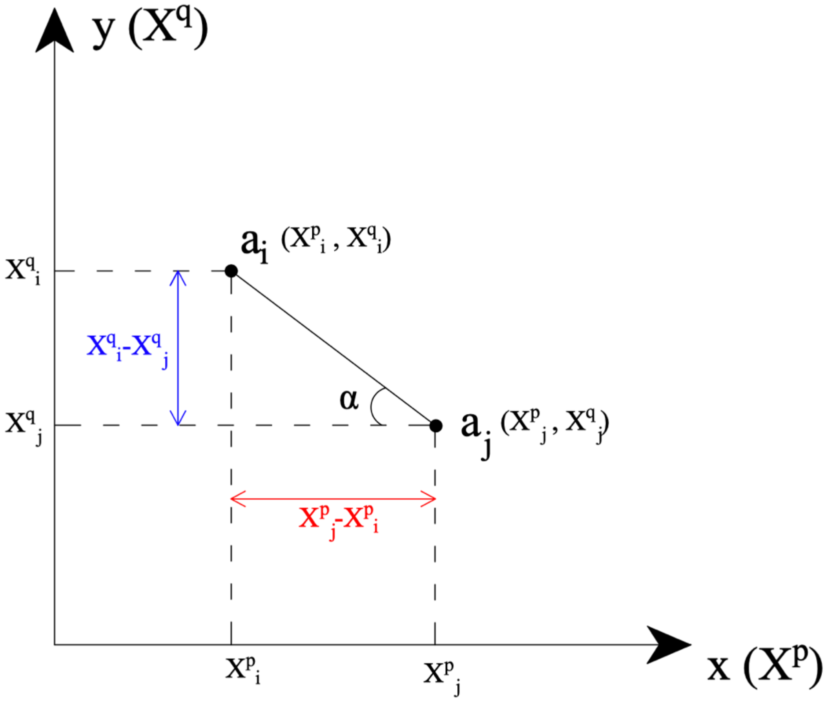
The point-to-point trade-offs can be shown in a two-dimensional (2D) graph as Figure A-1. According to Equation 6.7, trade-off between attributes X^p and X^p equals the cotangent of angle α. Therefore, the smaller angle α, the bigger the trade-off. The scenario of trade-offs with different angle α is summarised as below:

Scenario 1: When $\alpha = 45°$, $T_{ji}^{pq} = cot\alpha = 1$, meaning the amount of increase on X^p is the same as the amount of decrease on X^q. Therefore, the total evaluation values regarding X^p and X^q of alternative a_j and a_i are the same.

Scenario 2: When $0° < \alpha < 45°$, $T_{ji}^{pq} = cot\alpha > 1$, meaning the amount of increase on X^p is more than the amount of decrease on X^q when alternative a_i is replaced by alternative a_j. Therefore, the total evaluation value regarding X^p and X^q of alternative a_j is bigger than that of a_i.

Scenario 3: When $45° < \alpha < 90°$, $T_{ji}^{pq} = cot\alpha < 1$, meaning the amount of increase on X^p is less than the amount of decrease on X^q. Therefore, the total evaluation value regarding X^p and X^q of alternative a_j is smaller than that of a_i.

Figure A-1. A 2D expression of point-to-point trade-offs



Among the above three scenarios, Scenario 2 is the most preferable since the “price” to reach the same amount of improvement on attribute X^p is the smallest – the least decrease on attribute X^q. In this case, the total evaluation value of attribute X^p and X^q is the biggest among the three scenarios. The extreme case of Scenario 2 is when angle α is close to 0º, so there is almost no decrease on attribute X^q, but the same amount of increase on attribute X^p as in Scenarios 1 and 3. In this case, the line between a_i and a_j approximately parallels axis X in Figure A-1.

When there are three attributes that need to be considered at the same time, such as the three sustainability pillars, the process for looking for an alternative that can maximise trade-offs between the three is complicated. A three-dimensional (3D) graph as Figure A-2 shows is used to intuitively illustrate the trade-offs between three attributes.

Figure A-2. A 3D expression of trade-offs between three attributes

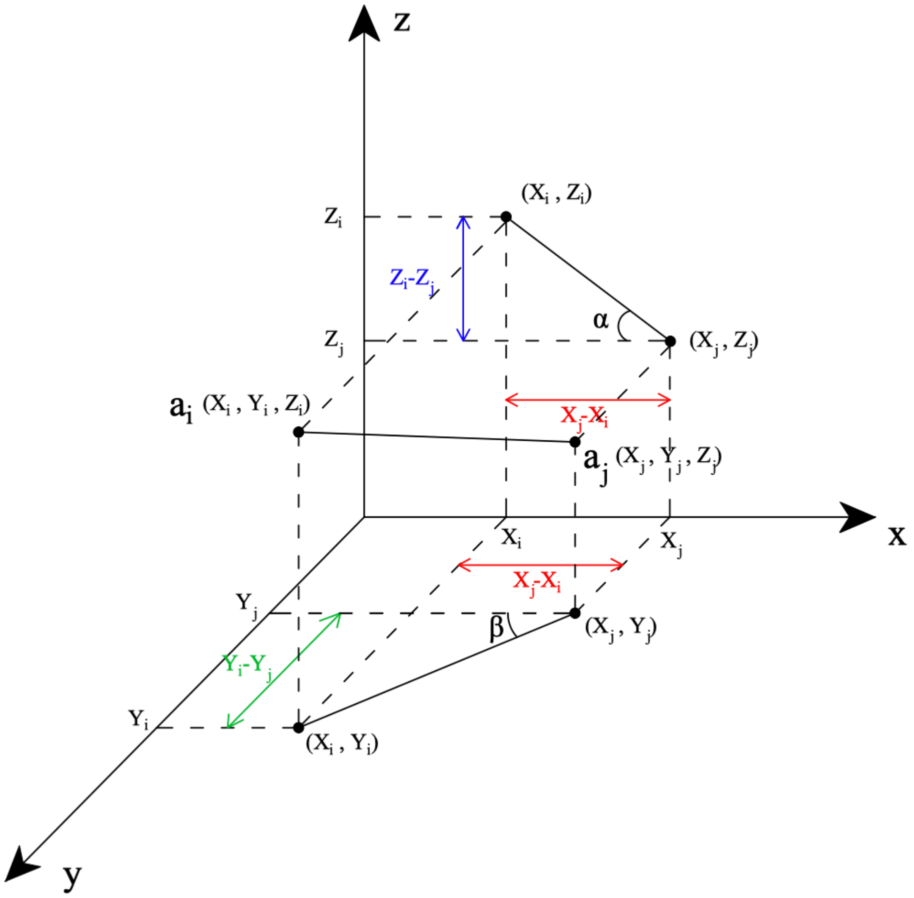


Figure A-2 illustrates a trade-off occurs between three attributes when the alternative a_i is analysed and it is realised that the evaluation regarding attribute X should be improved while the evaluation regarding attribute Y and attribute Z can be decreased. Therefore, there is no doubt that another alternative a_j'' is preferable if the evaluation $X_{j''}>X_i$, $Y_{j''} \geq Y_i$, and $Z_{j''} \geq Z_i$. If evaluation of alternative a_j' regarding attribute Y or Z is less than that of alternative a_i, it is a point-to-point trade-off as Figure A-1 shows. If no a_j'' or a_j' can be found, alternative a_j should be looked for which can maximise the trade-off between attributes X, Y and Z, as Equation A-1 shows.

$$\begin{cases} T_{ji}^{XY} = \frac{X_j - X_i}{Y_i - Y_j} \\ T_{ji}^{XZ} = \frac{X_j - X_i}{Z_i - Z_j} \end{cases} \qquad \text{Equation A-1}$$

Where,

T_{ji}^{XY} – trade-off between a pair of attributes X and Y when alternative a_i is replaced by the alternative a_j

T_{ji}^{XZ} – trade-off between a pair of attributes X and Z when alternative a_i is replaced by the alternative a_j

$Y_i - Y_j$ – value decrease in attribute Y when alternative a_i is replaced by the alternative a_j

$Z_i - Z_j$ – value decrease in attribute Z when alternative a_i is replaced by the alternative a_j

Based on the analysis of point-to-point trade-offs, the desired trade-off between three attributes should be the one where both angle α and β in Figure A-2 are between 0º and 45º, making the increase in attribute X bigger than the decrease in attributes Y and Z respectively. The extreme case is that the line between a_i and a_j approximately parallels axis X in Figure A-2. Therefore, the optimum solution is that the total evaluation value of attributes X, Y and Z is the biggest among all possible trade-off situations with three attributes considered.

Appendix B-1. Information letter and consent form for online questionnaire survey

INFORMATION SHEET AND CONSENT FORM FOR ONLINE SURVEYS

ETH 18-2810 – Developing a strategic assessment model of retrofitting for existing office buildings – A triple-bottom line approach

What is the research study about?

The purpose of this research is to develop a strategic assessment model of retrofitting for existing office buildings to improve their sustainability performance. The developed assessment model has the ability to assess the performance of existing office buildings from environmental, economic and social perspectives and identify suitable retrofitting activities. For this purpose, I will be conducting the questionnaire survey with seven different roles related to professionals in the construction industry, including building owners, contractors, project managers, architects, engineers, facility managers and tenants, to identify assessment variables. Then, based on the resulting assessment outcomes, suitable retrofitting strategies can be generated by the developed model.

You have been invited to participate because you are recognised having related life experience or professional experience of using office buildings or/and retrofitting buildings.

Who is conducting this research?

My name is Chenyang Li, and I am a PhD student at UTS. My supervisor are Associate Professor Grace Ding (Grace.Ding@uts.edu.au), Dr. Goran Runeson (Karl.Runeson@uts.edu.au) and Associate Professor Xiaoyu Ying (yingxiaoyu@zucc.edu.cn).

Inclusion/Exclusion Criteria

Before you decide to participate in this research study, we need to ensure that it is ok for you to take part.

If you satisfy at least one of the below criteria, you are included in this study.

- You are used to work/currently working as a contractor of building construction projects.
- You are used to work/currently working as a project manager of building constructions projects.
- You are used to work/currently working as a facility manager of an office building.
- You are used to work/currently working as an architect.
- You are used to work/currently working as a construction engineer.
- You are used to own/currently owning an office building.
- You are used to use/currently using at least one office building.

Do I have to take part in this research study?

Participation in this study is voluntary. It is completely up to you whether or not you decide to take part.

If you decide to participate, I will invite you to

- Read the information carefully;
- Complete an online questionnaire.

You can change your mind at any time and stop completing the surveys without consequences.

Are there any risks/inconvenience?

We don't expect this questionnaire to cause any harm or discomfort, however if you experience feelings of distress as a result of participation in this study you can let the researcher know and they will provide you with assistance.

What will happen to information about me?

Access to the online questionnaire is via a generic web link. Submission of the online questionnaire is an indication of your consent. By clicking the web link you consent to the research team collecting and using personal information about you for the research project. All this information will be treated confidentially. The collected information will be stored using codes, and all names or identity information will be represented by codes as well like participant A. The collected information and analysis document will be separately stored in hard drives, and the hard drives will also be locked in different lockers. Only the researcher will access the provided information.

We would like to store your information for future use in research projects that are an extension of this research project. In all instances your information will be treated confidentially. In any publication, information will be provided in such a way that you cannot be identified.

What if I have concerns or a complaint?

If you have concerns about the research that you think I or my supervisor can help you with, please feel free to contact us on Chenyang.Li@student.uts.edu.au, Grace.Ding@uts.edu.au, Karl.Runeson@uts.edu.au, yingxiaoyu@zucc.edu.cn.

If you would like to talk to someone who is not connected with the research, you may contact the Research Ethics Officer on 02 9514 9772 or Research.ethics@uts.edu.au and quote this number ETH 18-2810.

Appendix B-2. Questionnaire survey (English version)

Part I. General information

1. What is your gender?

☐ Male
☐ Female

2. Your age fits in which of the following groups?

☐ < 25 years old
☐ 26 – 35 years old
☐ 36 – 45 years old
☐ 46 – 55 years old
☐ > 55 years old

3. How many years have you been in the property management industry?

☐ < 5 years
☐ 6 – 10 years
☐ 11 – 15 years
☐ 16 – 20 years
☐ > 20 years

4. Which one(s) of the following best describes your role? (You can choose more than one)

☐ Building owner
☐ Project manager
☐ Facilities manager
☐ Architect
☐ Engineer
☐ Tenant
☐ Other __________

5. How often do you participate in the retrofitting of projects?

☐ Always
☐ Very often
☐ Sometimes
☐ Rarely
☐ Never

6. In the past three years, in how many retrofitting projects have you been involved in?

☐ 0
☐ 1- 3
☐ 4 – 7
☐ 8 – 11
☐ 12 – 14
☐ More than 14

7. What kinds of building have you retrofitted?

☐ Residential building
☐ Industrial building
☐ School building
☐ Other ________
☐ Office building
☐ Shopping mall
☐ Hospital building

Part II. Development of sustainable retrofitting

8. What are the activities you have been involved in the retrofitting of buildings? (You can choose more than one)

☐ Installing/upgrading insulation of building envelopes
☐ Adopting extensive green roof
☐ Changing windows to energy efficient windows
☐ Installing sun shading devices
☐ Installing building management control system (BMCS)
☐ Upgrading lifts to more energy efficient ones
☐ Upgrading HVAC system
☐ Upgrading lighting system
☐ Installing PV panel
☐ Installing water control sensors
☐ Replacing existing water fixtures with water efficient ones
☐ Installing water treatment system
☐ Other _____________

9. Do you use any tools to assess the performance of existing buildings after retrofitting? (You can choose more than one)

☐ NABERS (AU)

☐ LEED (USA)

☐ ASGB (CN)

☐ Other ________

☐ BREEAM (UK)

☐ GreenStar (AU)

☐ None

10. In your opinion, who is responsible for improving sustainability? (You can choose more than one)

☐ Government through regulation

☐ Government and industry jointly

☐ Other_________________

☐ Government through financial incentives

☐ Individual owners and managers

11. In your opinion, what are the drivers of retrofitting of buildings? (You can choose more than one)

☐ Tenants' requirement

☐ Economic payback

☐ Market request

☐ Other ____________

☐ Government

☐ Images/Branding

☐ Support and promotion from related organisations

Part III. Importance level of different aspects of sustainability

12. Could you rate the level of importance of the following aspects that could be considered in the retrofitting of buildings?

	Not important	Slightly important	Moderately important	Important	Very important
Environmental	☐	☐	☐	☐	☐
Economic	☐	☐	☐	☐	☐
Social	☐	☐	☐	☐	☐

Please specify if there are other aspects you think should be added.

____

13. When retrofitting an office building, what environmental concerns will you consider?

	Not important	**Slightly important**	**Moderately important**	**Important**	**Very important**
1. Reduce energy consumption	☐	☐	☐	☐	☐
2. Reduce carbon emissions	☐	☐	☐	☐	☐
3. Use reusable or recyclable materials or components	☐	☐	☐	☐	☐
4. Reduce waste generation	☐	☐	☐	☐	☐
5. Improve indoor environmental quality	☐	☐	☐	☐	☐
6. Reduce impacts on water resources	☐	☐	☐	☐	☐

Please specify if there are other aspects you think should be added.

____

14. Please rate the below social parameters for sustainable assessment of retrofitting.

	Not important	**Slightly important**	**Moderately important**	**Important**	**Very important**
1. Noise impact on the neighbourhood	☐	☐	☐	☐	☐
2. Emission impact on the neighbourhood (e.g., particulates, odour, water and heat)	☐	☐	☐	☐	☐
3. Impact from glare or overshadowing neighbourhood	☐	☐	☐	☐	☐
4. Safety and security	☐	☐	☐	☐	☐
5. Impact on cultural heritage	☐	☐	☐	☐	☐
6. Accessibility to building facilities for people with special needs	☐	☐	☐	☐	☐
7. Accessibility to building services	☐	☐	☐	☐	☐
8. Impact on maintenance and maintainability from newly added building fabrics or building systems	☐	☐	☐	☐	☐

Please specify if there are other aspects you think should be added.

Part IV. Further discussion about improvement of sustainable retrofitting

15. Based on your experience as a user/owner of office building(s), what do you expect to be improved by sustainable retrofitting? (If it is not relevant to your experience, please skip this question)

16. Based on your professional experience as a participant who works on a building retrofitting project, which parts of the office building should be included for improving the overall sustainability? (If it is not relevant to your experience, please skip this question)

17. In addition to retrofitting, are there other actions that should be taken to improve the performance of existing buildings?

Appendix B-3. Questionnaire survey (Chinese version)

一、基本信息

1. 您的性别是什么？

□ 男
□ 女

2. 您的年龄在以下那个年龄区间？

□ < 25 岁
□ 26 – 35 岁
□ 36 – 45 岁
□ 45 – 55 岁
□ >55 岁

3. 您已在建筑与房屋管理领域从业多少年？

□ < 5 年
□ 6 – 10 年
□ 11 – 15 年
□ 16 – 20 年
□ > 20 年

4. 您从事过或正在从事以下哪个领域？（可以选择一个以上的选项）

□ 建筑拥有者
□ 项目经理
□ 建筑师
□ 工程师
□ 物业管理
□ 租户
□ 其他_________

5. 您参与房屋翻新项目的频率大概是什么？

□ 很频繁
□ 很少
□ 偶尔
□ 从来没有
□ 经常

6. 在过去三年里，您参与过多少个房屋翻新项目？

□ 0
□ 1 – 3
□ 4 – 7
□ 8 – 11
□ 12 – 14
□ 多于 14

7. 您参与过以下哪种类型建筑的翻新项目？（可以选择一个以上的选项）

□ 居住建筑
□ 办公建筑
□ 工业建筑
□ 商场
□ 教学建筑
□ 医院
□ 其他________

二、对于绿色翻新的认知

8. 您曾经参与过的房屋翻新项目中，采用过以下哪些翻新措施？（可以选择一个以上的选项）

□ 安装/更换外围护保温层
□ 使用绿色屋顶
□ 更换为节能窗户
□ 安装遮阳装置
□ 安装建筑管理控制系统
□ 更换为节能电梯
□ 更换空调通风系统
□ 更换照明系统
□ 使用太阳能
□ 安装水控制传感器
□ 更换小便池、马桶和水龙头等为节水装置
□ 安装水处理系统
□ 其他_____________

9. 您用过以下哪些房屋评价系统？（可以选择一个以上的选项）

□ NABERS (澳洲)
□ BREEAM (英国)
□ LEED (美国)
□ GreenStar (澳洲)
□ ASGB (中国)
□ 没有使用过
□ 其他 ________

10. 您认为以下哪些对象有责任推广绿色建筑？（可以选择一个以上的选项）

□ 政府通过颁布和执行相关规范从而提高绿色建筑的表现力

□ 政府通过经济刺激推广绿色建筑业

□ 政府和企业共同负责

□ 个人和管理者负责

□ 其他 ________________

11. 您认为以下哪些方面主导着房屋翻新行业？（可以选择一个以上的选项）

□ 租户的需求

□ 经济回报

□ 市场需求

□ 企业形象

□ 相关机构和组织

□ 政府

□ 其他 ________________

三、绿色翻新整修的评价参数

12. 请您为以下关于绿色建筑的几个方面进行重要性等级划分。

	不重要	有一些重要	中等重要	重要	非常重要
环境	□	□	□	□	□
经济	□	□	□	□	□
社会	□	□	□	□	□

除了以上5个方面，如果您认为还有关于绿色建筑的其他方面需要考虑，请在此说明。

13. 在实施房屋翻新时，需要考虑的环境问题有哪些？并请为它们的重要性进行等级划分。

	不重要	有一些重要	中等重要	重要	非常重要
1. 减少能耗	□	□	□	□	□
2. 减少碳排放	□	□	□	□	□
3. 使用可重复利用或可回收使用的材料或部件	□	□	□	□	□
4. 减少垃圾的产生	□	□	□	□	□
5. 提高室内环境质量	□	□	□	□	□
6. 减少对水资源的影响	□	□	□	□	□

除了以上 7 个方面，在实施房屋翻新时，如果您认为还有其他环境问题需要考虑，请在此说明。

14. 在实施房屋翻新时，需要考虑的社会因素有哪些？并请为它们的重要性进行等级划分。

	不重要	有一些重要	中等重要	重要	非常重要
1. 噪声对毗邻建筑的影响	□	□	□	□	□
2. 排放物对毗邻建筑的影响（例如：颗粒物、气味、水喝热量的排放）	□	□	□	□	□
3. 对毗邻建筑的光污染或过分遮挡	□	□	□	□	□
4. 安全性	□	□	□	□	□
5. 对历史文化的影响	□	□	□	□	□
6. 是否有为特殊人群（残疾人、孕妇、老人和孩子）提供的建筑设施	□	□	□	□	□
7. 是否有相应的建筑物设施以供使用	□	□	□	□	□

8. 新安装建筑材料或建筑系统对建筑维修和围护的频率和时间的影响（包括建筑翻新）	□	□	□	□	□

除了以上 10 个社会因素，如果您认为在房屋翻新时，还有其他社会因素需要考虑，请在此说明。

四、对提高绿色翻新整修的进一步讨论

15．根据您作为建筑拥有者或者使用者的经验，您期望建筑翻新时可以改善建筑的哪些方面？（如果您不是建筑拥有者或使用者，请忽略此题。）

16. 根据您相关的从业经验，您认为在建筑翻新过程中需要考虑哪些方面去提高建筑的可持续性？（如果您不是建筑师、工程师、项目经理或者物业从业人员，请忽略此题。）

17. 除了建筑翻新，您认为还可以采取哪些措施来提高既有建筑的可持续性？

Appendix B-4. Chi-Square test for association between region and commonly used retrofitting activities

(1) Region and installing/upgrading insulation of external walls

Crosstab		
Retrofitting activity / Region	Installing/upgrading insulation of external walls	
	Count	% of Total
Northern China	46	35.9%
Southern China	20	15.6%
Total	66	51.6%

Chi-Square Tests					
	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	10.012[a]	1	.002		
Continuity Correction[b]	8.915	1	.003		
Likelihood Ratio	10.140	1	.001		
Fisher's Exact Test				.002	.001
N of Valid Cases	128				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 27.13.

b. Computed only for a 2x2 table

(2) Region and adopting extensive green roof

Crosstab

Retrofitting activity Region	Adopting extensive green roof	
	Count	% of Total
Northern China	26	20.3%
Southern China	19	14.8%
Total	45	35.2%

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	1.329[a]	2	.514
Likelihood Ratio	1.697	2	.6428
N of Valid Cases	128		

a. 2 cells (33.3%) have expected count less than 5. The minimum expected count is .44.

(3) Region and changing windows to energy efficient windows

Crosstab		
Retrofitting activity Region	Changing windows to energy efficient windows	
	Count	% of Total
Northern China	25	19.5%
Southern China	14	10.9%
Total	39	30.5%

Chi-Square Tests					
	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	1.405[a]	1	.236		
Continuity Correction[b]	0.984	1	.321		
Likelihood Ratio	1.421	1	.233		
Fisher's Exact Test				.253	.161
N of Valid Cases	128				

a. 2 cells (50.0%) have expected count less than 5. The minimum expected count is 17.06.

b. Computed only for a 2x2 table

(4) Region and installing sun shading devices

Crosstab		
Retrofitting activity Region	Installing sun shading devices	
	Count	% of Total
Northern China	4	3.1%
Southern China	15	11.7%
Total	19	14.8%

Chi-Square Tests					
	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	11.232[a]	1	.001		
Continuity Correction[b]	9.615	1	.002		
Likelihood Ratio	11.526	1	.001		
Fisher's Exact Test				.001	.001
N of Valid Cases	128				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 8.31.

b. Computed only for a 2x2 table

(5) Region and installing building management control system

Crosstab		
Retrofitting activity / Region	Installing building management control system	
	Count	% of Total
Northern China	7	5.5%
Southern China	10	7.8%
Total	17	13.3%

Chi-Square Tests					
	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	1.810[a]	1	.179		
Continuity Correction[b]	1.173	1	.279		
Likelihood Ratio	1.795	1	.180		
Fisher's Exact Test				.199	.140
N of Valid Cases	128				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 7.44.

b. Computed only for a 2x2 table

(6) Region and upgrading lifts to more energy efficient ones

Crosstab		
Retrofitting activity Region	Upgrading lifts to more energy efficient ones	
	Count	% of Total
Northern China	37	28.9%
Southern China	35	27.3%
Total	72	56.3%

Chi-Square Tests					
	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	1.580[a]	1	.209		
Continuity Correction[b]	1.161	1	.281		
Likelihood Ratio	1.588	1	.208		
Fisher's Exact Test				.281	.141
N of Valid Cases	128				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 24.50.

b. Computed only for a 2x2 table

(7) Region and upgrading HVAC

Crosstab		
Retrofitting activity / Region	Upgrading HVAC	
	Count	% of Total
Northern China	12	9.4%
Southern China	25	19.5%
Total	37	28.9%

Chi-Square Tests					
	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	11.997[a]	1	.001		
Continuity Correction[b]	10.674	1	.001		
Likelihood Ratio	12.066	1	.001		
Fisher's Exact Test				.001	.001
N of Valid Cases	128				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 16.19.

b. Computed only for a 2x2 table

(8) Region and upgrading lighting system

Crosstab		
Retrofitting activity / Region	Upgrading lighting system	
	Count	% of Total
Northern China	22	17.2%
Southern China	28	21.9%
Total	50	39.1%

Chi-Square Tests					
	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	5.003[a]	1	.025		
Continuity Correction[b]	4.220	1	.040		
Likelihood Ratio	5.007	1	.025		
Fisher's Exact Test				.030	.020
N of Valid Cases	128				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 21.88.

b. Computed only for a 2x2 table

(9) Region and installing PV panels

Crosstab		
Retrofitting activity Region	Installing PV panels	
	Count	% of Total
Northern China	36	28.1%
Southern China	20	15.6%
Total	56	43.8%

Chi-Square Tests					
	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	2.612[a]	1	.106		
Continuity Correction[b]	2.064	1	.151		
Likelihood Ratio	2.631	1	.105		
Fisher's Exact Test				.151	.075
N of Valid Cases	128				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 24.50.

b. Computed only for a 2x2 table

(10) Region and installing water control system

Crosstab		
Retrofitting activity Region	Installing water control system	
	Count	% of Total
Northern China	8	6.3%
Southern China	7	5.5%
Total	15	11.7%

Chi-Square Tests					
	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	.059[a]	1	.809		
Continuity Correction[b]	.000	1	1.000		
Likelihood Ratio	.059	1	.809		
Fisher's Exact Test				1.000	.510
N of Valid Cases	128				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 6.56.

b. Computed only for a 2x2 table

(11) Region and replacing existing water fixtures with water efficient ones

Crosstab		
Retrofitting activity / Region	Changing existing water fixtures with water efficient ones	
	Count	% of Total
Northern China	23	18.0%
Southern China	21	16.4%
Total	44	34.4%

Chi-Square Tests					
	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	.431[a]	1	.512		
Continuity Correction[b]	.220	1	.639		
Likelihood Ratio	.430	1	.512		
Fisher's Exact Test				.575	.319
N of Valid Cases	128				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 19.25.

b. Computed only for a 2x2 table

(12) Region and installing a water treatment system

Crosstab		
Retrofitting activity / Region	Installing a water treatment system	
	Count	% of Total
Northern China	10	7.8%
Southern China	16	12.5%
Total	26	20.3%

Chi-Square Tests					
	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	4.195[a]	1	.041		
Continuity Correction[b]	3.337	1	.068		
Likelihood Ratio	4.175	1	.041		
Fisher's Exact Test				.048	.034
N of Valid Cases	128				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 11.38.

b. Computed only for a 2x2 table

Appendix B-5. Chi-Square test for association between importance level of environmental assessment criteria and whether respondents have ever conducted projects involving office buildings

(1) Retrofitted building types and importance level of reduce energy consumption

Crosstab					
Importance level / Building type	Reduce energy consumption				
	Slightly important	Moderately important	Important	Very important	Total
Office buildings	1	2	22	19	44
Others	2	8	34	40	84
Total	3	10	56	59	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	1.639[a]	3	.650
Likelihood Ratio	1.715	3	.634
Linear-by-linear Association	.003	1	.955
N of Valid Cases	128		

a. 3 cells (37.5%) have expected count less than 5. The minimum expected count is 1.03.

(2) Retrofitted building types and importance level of reduce carbon emission

Crosstab						
Importance level Building type	Reduce carbon emission					
	Not important	Slightly important	Moderately important	Important	Very important	Total
Office buildings	0	1	4	11	28	44
Others	1	1	8	30	44	84
Total	1	2	12	41	72	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	2.431[a]	4	.657
Likelihood Ratio	2.770	4	.597
Linear-by-linear Association	.795	1	.372
N of Valid Cases	128		

a. 5 cells (50%) have expected count less than 5. The minimum expected count is .34.

(3) Retrofitted building types and importance level of use reusable or recyclable materials or components

Crosstab

Importance level / Building type	Use reusable or recyclable materials or components					
	Not important	Slightly important	Moderately important	Important	Very important	Total
Office buildings	1	1	10	22	10	44
Others	1	3	22	35	23	84
Total	2	4	32	57	33	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	1.204[a]	4	.877
Likelihood Ratio	1.200	4	.878
Linear-by-linear Association	.013	1	.910
N of Valid Cases	128		

a. 4 cells (40.0%) have expected count less than 5. The minimum expected count is .69.

(4) Retrofitted building types and importance level of reduce waste generation

Crosstab						
Importance level Building type	Reduce waste generation					
	Not important	Slightly important	Moderately important	Important	Very important	Total
Office buildings	0	2	6	22	14	44
Others	2	2	10	45	25	84
Total	2	4	16	67	39	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	1.660[a]	4	.798
Likelihood Ratio	2.275	4	.685
Linear-by-linear Association	.041	1	.840
N of Valid Cases	128		

a. 4 cells (40.0%) have expected count less than 5. The minimum expected count is .69.

(5) Retrofitted building types and importance level of improve indoor environmental quality

Crosstab

Importance level Building type	Improve indoor environmental quality				
	Slightly important	Moderately important	Important	Very important	Total
Office buildings	0	3	11	30	44
Others	1	8	26	49	84
Total	1	11	37	79	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	1.577[a]	3	.665
Likelihood Ratio	1.907	3	.592
Linear-by-linear Association	1.364	1	.243
N of Valid Cases	128		

a. 3 cells (37.5%) have expected count less than 5. The minimum expected count is .34.

(6) Retrofitted building types and importance level of reduce impacts on water resources

Crosstab

Importance level Building type	Reduce impacts on water resources				
	Slightly important	Moderately important	Important	Very important	Total
Office buildings	1	2	11	24	44
Others	1	9	34	40	84
Total	2	11	51	64	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	1.797[a]	3	.616
Likelihood Ratio	1.926	3	.588
Linear-by-linear Association	.682	1	.409
N of Valid Cases	128		

a. 3 cells (37.5%) have expected count less than 5. The minimum expected count is .69.

Appendix B-6. Chi-Square test for association between importance level of social assessment criteria and whether respondents have ever conducted projects involving office buildings

(1) Retrofitted building types and importance level of noise impact on the neighbourhood

Crosstab				
Importance level / Building type	Noise impact on the neighbourhood			
	Moderately important	Important	Very important	Total
Office buildings	6	26	12	44
Others	11	38	35	84
Total	17	64	47	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	2.744[a]	2	.254
Likelihood Ratio	2.798	2	.247
Linear-by-linear Association	1.436	1	.231
N of Valid Cases	128		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 5.84.

(2) Retrofitted building types and importance level of emission impact on the neighbourhood

Crosstab				
Importance level Building type	Emission impact on the neighbourhood			
	Moderately important	Important	Very important	Total
Office buildings	5	24	15	44
Others	10	34	40	84
Total	15	58	55	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	2.498[a]	2	.287
Likelihood Ratio	2.511	2	.285
Linear-by-linear Association	1.076	1	.300
N of Valid Cases	128		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 5.16.

(3) Retrofitted building types and importance level of impact from glare or overshadowing neighbourhood

Crosstab				
Importance level / Building type	Impact from glare or overshadowing neighbourhood			
	Moderately important	Important	Very important	Total
Office buildings	4	29	11	44
Others	9	40	35	84
Total	13	69	46	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	4.099[a]	2	.129
Likelihood Ratio	4.185	2	.123
Linear-by-linear Association	1.644	1	.200
N of Valid Cases	128		

a. 1 cells (16.7%) have expected count less than 5. The minimum expected count is 4.47.

(4) Retrofitted building types and importance level of safety and security

Crosstab

Importance level / Building type	Safety and security				
	Slightly important	Moderately important	Important	Very important	Total
Office buildings	1	3	16	24	44
Others	1	3	27	53	84
Total	2	6	43	77	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	1.370[a]	3	.713
Likelihood Ratio	1.330	3	.722
Linear-by-linear Association	1.278	1	.258
N of Valid Cases	128		

a. 4 cells (50%) have expected count less than 5. The minimum expected count is .69.

(5) Retrofitted building types and importance level of impact on cultural heritage

Crosstab				
Importance level / Building type	Impact on cultural heritage			
	Moderately important	Important	Very important	Total
Office buildings	10	22	12	44
Others	10	42	32	84
Total	20	64	44	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	3.148[a]	2	.207
Likelihood Ratio	3.077	2	.215
Linear-by-linear Association	2.888	1	.089
N of Valid Cases	128		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 6.88.

(6) Retrofitted building types and importance level of accessibility to building facilities for people with special needs

Crosstab

Importance level / Building type	Accessibility to building facilities for people with special needs					
	Not important	Slightly important	Moderately important	Important	Very important	Total
Office buildings	1	0	4	20	19	44
Others	1	2	11	32	38	84
Total	2	2	15	52	57	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	2.072[a]	4	.723
Likelihood Ratio	2.708	4	.608
Linear-by-linear Association	.049	1	.825
N of Valid Cases	128		

a. 4 cells (40.0%) have expected count less than 5. The minimum expected count is .69.

(7) Retrofitted building types and importance level of accessibility to building services

Crosstab

Importance level / Building type	Accessibility to building services				
	Slightly important	Moderately important	Important	Very important	Total
Office buildings	2	7	27	8	44
Others	2	14	43	25	84
Total	4	21	70	33	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	2.491[a]	3	.477
Likelihood Ratio	2.549	3	.466
Linear-by-linear Association	1.205	1	.272
N of Valid Cases	128		

a. 2 cells (25%) have expected count less than 5. The minimum expected count is 1.38.

(8) Retrofitted building types and importance level of impact on maintenance and maintainability from newly added building fabrics or building systems

Crosstab					
Importance level Building type	Impact on maintenance and maintainability from newly added building fabrics or building systems				
	Slightly important	Moderately important	Important	Very important	Total
Office buildings	0	8	26	10	44
Others	1	14	40	29	84
Total	1	22	66	39	128

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	2.618[a]	3	.454
Likelihood Ratio	2.987	3	.384
Linear-by-linear Association	.693	1	.405
N of Valid Cases	128		

a. 2 cells (25.0%) have expected count less than 5. The minimum expected count is .34.

Appendix C-1. Information letter for focus group discussions (English version)

PARTICIPANT INFORMATION SHEET

Developing a strategic assessment model of retrofitting for existing office buildings – A triple-bottom line approach (UTS NUMBER ETH-2810)

WHO IS DOING THE RESEARCH?

My name is Chenyang Li and I am a PhD student at UTS. My supervisor is Associate Professor Grace, Dr. Goran Runeson and Associate Professor Xiaoyu Ying.

WHAT IS THIS RESEARCH ABOUT?

This research is to find out about developing a strategic assessment model of retrofitting for existing office buildings to improve their sustainability performance. The developed assessment model has the ability to assess the performance of existing office buildings from environmental, economic and social perspectives and identify suitable retrofitting activities. For this purpose, I will be conducting the questionnaire survey with seven different roles related to professionals in the construction industry, including building owners, contractors, project managers, architects, engineers, facility managers and tenants, to identify assessment variables. Then, based on the resulting assessment outcomes, suitable retrofitting strategies can be generated by the developed model.

FUNDING

There is no funding received for this research.

WHY HAVE I BEEN ASKED?

You have been invited to participate in this study because you are a professional or stakeholder of building industry, and you are able to provide the information based on your knowledge and experience that I need to complete my research.

IF I SAY YES, WHAT WILL IT INVOLVE?

If you decide to participate, I will invite you to participate in a focus group that will take approximately 60 minutes of your time at your convenience.

ARE THERE ANY RISKS/INCONVENIENCE?

Yes, there are some risks/inconvenience. They are:

- Inconvenience of time taken to undertake this focus group
- May leave the workplace during work time for undertaking this focus group
- Feeling uncomfortable being recorded
- Feeling uncomfortable being speaking in a group

DO I HAVE TO SAY YES?

Participation in this study is voluntary. It is completely up to you whether or not you decide to take part.

WHAT WILL HAPPEN IF I SAY NO?

If you decide not to participate, it will not affect your relationship with the researchers or the University of Technology Sydney. If you wish to withdraw from the study once it has started, you can do so at any time without having to give a reason, by contacting Chenyang Li (Chenyang.Li@student.uts.edu.au).

If you withdraw from the study, your audio tape will be erased, the transcripts will be destroyed and all your information will be destroyed as well.

CONFIDENTIALITY

By signing the consent form you consent to the research team collecting and using personal information about you for the research project. All this information will be treated confidentially. The collected information will be stored using codes, and all names or identity information will be represented by codes as well like participant A. The collected information and analysis document will be separately stored in hard drives, and the hard drives will also be locked in different lockers. Your information will only be used for the purpose of this research project.

We would like to store your information for future use in research projects that are an extension of this research project. In all instances your information will be treated confidentially. In any publication, information will be provided in such a way that you cannot be identified.

WHAT IF I HAVE CONCERNS OR A COMPLAINT?

If you have concerns about the research that you think I or my supervisor can help you with, please feel free to contact us on Chenyang.Li@student.uts.edu.au, Grace.Ding@uts.edu.au, Karl.Runeson@uts.edu.au, yingxiaoyu@zucc.edu.au.

You will be given a copy of this form to keep.

NOTE:

This study has been approved by the University of Technology Sydney Human Research Ethics Committee [UTS HREC]. If you have any concerns or complaints about any aspect of the conduct of this research, please contact the Ethics Secretariat on ph.: +61 2 9514 2478 or email: Research.Ethics@uts.edu.au], and quote the UTS HREC reference number. Any matter raised will be treated confidentially, investigated and you will be informed of the outcome.

Appendix C-2. Consent form for focus group discussions (English version)

CONSENT FORM

Developing a strategic assessment model of retrofitting for existing office buildings – A triple-bottom line approach (ETH18-2810)

I ____________________ *(participant's name)* agree to participate in the research project "Developing a strategic assessment model of retrofitting for existing office buildings – A triple-bottom line approach" *(UTS HREC reference number: ETH18-2810)* being conducted by Chenyang Li (15 Broadway, Ultimo, NSW 2007, contact telephone: [redacted]).

I have read the Participant Information Sheet or someone has read it to me in a language that I understand.

I understand the purposes, procedures and risks of the research as described in the Participant Information Sheet.

I have had an opportunity to ask questions and I am satisfied with the answers I have received.

I freely agree to participate in this research project as described and understand that I am free to withdraw at any time without affecting my relationship with the researchers or the University of Technology Sydney.

I understand that I will be given a signed copy of this document to keep.

I agree to be:

☐ Audio recorded

I agree that the research data gathered from this project may be published in a form that:

☐ Does not identify me in any way

☐ May be used for future research purposes

I am aware that I can contact Chenyang Li if I have any concerns about the research.

____ ____/____/____

Name and Signature [participant] Date

____ ____/____/____

Name and Signature [researcher or delegate] Date

* Witness to the consent process

If the participant, or if their legally acceptable representative, is not able to read this document, this form must be witnessed by an independent person over the age of 18. In the event that an interpreter is used, the interpreter may not act as a witness to the consent process. By signing the consent form, the witness attests that the information in the consent form and any other written information was accurately explained to, and apparently understood by, the participant (or representative) and that informed consent was freely given by the participant (or representative).

Appendix D-1. AHP survey sample

Please use the below scale to define the relative importance of the element A compared to element B

Intensity of Importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one over another
6	Strong plus	
7	Very strong or demonstrated importance	A criterion is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one over another is of the highest possible order of affirmation
Reciprocals of above	If criterion i has one of the above non-zero numbers assigned to it when compared with criterion j, then j has the reciprocal value when compared with i	A reasonable assumption
1.1 – 1.9	If the criteria are very close	It may be challenging to assign the best value, but when compared with other contrasting criteria, the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the criteria.

The lower left hand matrix triangle is the reciprocal of the upper right hand, so only the upper right hand needs to be filled in.

Part 1. The three sustainability dimensions

Table 1. The three sustainability dimensions

A/B	Environmental	Economic	Social
Environmental	1		
Economic		1	
Social			1

Part 2. The assessment criteria in the environmental dimension

Table 2. Assessment criteria in retrofitting stage of environmental dimension

A/B	Energy consumption	Carbon emissions	Use of recyclable/reusable materials	Waste generation
Energy consumption	1			
Carbon emissions		1		
Use of recyclable/reusable materials			1	
Waste generation				1

Table 3. Assessment criteria in operation stage of environmental dimension

A/B	Energy consumption	Carbon emissions	Use of recyclable/reusable materials	Waste generation	Indoor environmental quality	Water consumption
Energy consumption	1					
Carbon emissions		1				
Use of recyclable/reusable materials			1			
Waste generation				1		
Indoor environmental quality					1	
Water consumption						1

Part 3. The assessment criteria in the social dimension

Table 4. Assessment criteria in retrofitting stage of social dimension

A/B	Noise impact on neighbourhood	Emission impact on neighbourhood	Safety of retrofitting construction	Impact on cultural heritage	Impact on surrounding traffic and pedestrians	Impact on relocating tenants
Noise impact on neighbourhood	1					
Emission impact on neighbourhood		1				
Safety of retrofitting construction			1			
Impact on cultural heritage				1		
Impact on surrounding traffic and pedestrians					1	
Impact on relocating tenants						1

Table 5. Assessment criteria in operation stage of social dimension

A/B	Accessibility to building facilities for people with special needs	Accessibility to building services	Impacts on maintenance and maintainability from newly added building fabrics and building systems	Safety and security of users	Room flexibility for different demands
Accessibility to building facilities for people with special needs	1				
Accessibility to building services		1			
Impacts on maintenance and maintainability from newly added building fabrics and building systems			1		
Safety and security of users				1	
Room flexibility for different demands					1

Appendix D-2. Establishing the matrix of group judgment

Based on Equation 7.3 in Chapter 3, the matrix of group judgment on the three sustainability dimensions and assessment criteria is established as Table D2-1 to Table D2-5 illustrate.

Table D2-1. The matrix of group judgment on the three sustainability dimensions

Sustainability dimensions	Environmental	Economic	Social
Environmental	1	1.309	1.891
Economic	0.764	1	1.321
Social	0.529	0.757	1

Table D2-2. The matrix of group judgment on assessment criteria in the retrofitting stage of the environmental dimension

Environmental assessment criteria in retrofitting stage	Energy consumption	Carbon emissions	Potential for recyclable/reusable materials	Waste generation
Energy consumption	1	1.013	0.964	1.021
Carbon emissions	0.987	1	0.967	0.987
Potential for recyclable/reusable materials	1.037	1.034	1	0.925
Waste generation	0.980	1.013	1.082	1

Table D2-3. The matrix of group judgment on assessment criteria in operation stage of the environmental dimension

Environmental assessment criteria in operation stage	Energy consumption	Carbon emissions	Potential for recyclable/reusable materials	Waste generation	Indoor environmental quality	Water consumption
Energy consumption	1	1.523	1.301	1.409	1.182	1.830
Carbon emissions	0.657	1	1.026	1.082	0.818	1.265
Potential for recyclable/reusable materials	0.768	0.974	1	1.051	0.844	1.145
Waste generation	0.768	1.090	0.952	1	0.784	1.160
Indoor environmental quality	0.766	1.406	1.185	1.484	1	1.484
Water consumption	0.541	0.790	0.873	0.952	0.674	1

Table D2-4. The matrix of group judgment on assessment criteria in the retrofitting stage of the social dimension

Social assessment criteria in retrofitting stage	Noise impact on neighbourhood	Emission impact on neighbourhood	Safety of retrofitting construction	Impact on cultural heritage	Impact on surrounding traffic and pedestrians	Impact on relocating tenants
Noise impact on neighbourhood	1	0.910	0.604	1.026	0.891	0.952
Emission impact on neighbourhood	1.099	1	0.699	1.330	1.229	1.379
Safety of retrofitting construction	1.657	1.430	1	1.364	1.261	1.727
Impact on cultural heritage	0.974	0.752	0.733	1	0.976	1.037
Impact on surrounding traffic and pedestrians	1.122	0.813	0.793	1.024	1	1.275
Impact on relocating tenants	1.051	0.725	0.579	0.964	0.784	1

Table D2-5. The matrix of group judgment on assessment criteria in the operation stage of the social dimension

A/B	Accessibility to building facilities for people with special needs	Accessibility to building services	Impacts on maintenance and maintainability from newly added building fabrics and building systems	Safety and security of users	Room flexibility for different demands
Accessibility to building facilities for people with special needs	1	1.492	1.644	1.203	1.340
Accessibility to building services	0.670	1	0.993	0.774	0.845
Impacts on maintenance and maintainability from newly added building fabrics and building systems	0.608	1.008	1	0.795	0.807
Safety and security of users	0.381	1.292	1.258	1	1.343
Room flexibility for different demands	0.746	1.183	1.240	0.745	1

Appendix D-3. Weight generation

Table D3-1. The column normalised weights for the three sustainability dimensions

	Environmental	Economic	Social
Environmental	1.000	1.309	1.891
Economic	0.764	1.000	1.321
Social	0.529	0.757	1.000
Sum	**2.293**	**3.066**	**4.212**

Table D3-2. The line normalised weights for the three sustainability dimensions

	Environmental	Economic	Social	**Sum**	**Normalised weight**
Environmental	0.436	0.427	0.449	**1.312**	**0.437**
Economic	0.333	0.326	0.314	**0.973**	**0.324**
Social	0.231	0.247	0.237	**0.715**	**0.239**
Sum	**1**	**1**	**1**	**3**	**1**

Table D3-3. The column normalised weights for assessment criteria

Environmental dimension						
Retrofitting stage						
	Energy consumption	Carbon emissions	Potential for recyclable/reusable materials	Waste generation		
Energy consumption	1	1.013	0.964	1.021		
Carbon emissions	0.987	1	0.967	0.987		
Potential for recyclable/ reusable materials	1.037	1.034	1	0.925		
Waste generation	0.980	1.013	1.082	1		
Sum	**4.004**	**4.060**	**4.013**	**3.932**		
Operation stage						
	Energy consumption	Carbon emissions	Potential for recyclable/reusable materials	Waste generation	Indoor environmental quality	Water consumption
Energy consumption	1	1.523	1.301	1.409	1.182	1.830
Carbon emissions	0.657	1	1.026	1.082	0.818	1.265
Potential for recyclable/ reusable materials	0.768	0.974	1	1.051	0.844	1.145
Waste generation	0.768	1.090	0.952	1	0.784	1.160
Indoor environmental quality	0.766	1.406	1.185	1.484	1	1.484
Water consumption	0.541	0.790	0.873	0.952	0.674	1
Sum	**4.500**	**6.783**	**6.337**	**6.806**	**5.302**	**7.884**
Social dimension						
Retrofitting stage						
	Noise impact on neighbourhood	Emission impact on neighbourhood	Safety of retrofitting construction	Impact on cultural heritage	Impact on surrounding traffic and pedestrians	Impact on relocating tenants
Noise impact on neighbourhood	1	0.910	0.604	1.026	0.891	0.952
Emission impact on neighbourhood	1.099	1	0.699	1.330	1.229	1.379
Safety of retrofitting construction	1.657	1.430	1	1.364	1.261	1.727
Impact on cultural heritage	0.974	0.752	0.733	1	0.976	1.037
Impact on surrounding traffic and pedestrians	1.122	0.813	0.793	1.024	1	1.275
Sum	**6.903**	**5.630**	**4.408**	**6.708**	**6.141**	**7.370**

Operation stage						
A/B	Accessibility to building facilities for people with special needs	Accessibility to building services	Impacts on maintenance and maintainability from newly added building fabrics and building systems	Safety and security of users	Room flexibility for different demands	
Accessibility to building facilities for people with special needs	1	1.492	1.644	1.203	1.340	
Accessibility to building services	0.670	1	0.993	0.774	0.845	
Impacts on maintenance and maintainability from newly added building fabrics and building systems	0.608	1.008	1	0.795	0.807	
Safety and security of users	0.381	1.292	1.258	1	1.343	
Room flexibility for different demands	0.746	1.183	1.240	0.745	1	
Sum	**3.855**	**5.975**	**6.135**	**4.517**	**5.335**	

Table D3-4. The column normalised weights for assessment criteria

Environmental dimension								
Retrofitting stage								
	Energy consumption	Carbon emissions	Potential for recyclable/ reusable materials	Waste generation	**Sum**	**Normalised weight**		
Energy consumption	0.250	0.250	0.240	0.260	**0.999**	**0.25**		
Carbon emissions	0.247	0.246	0.241	0.251	**0.985**	**0.245**		
Potential for recyclable/ reusable materials	0.259	0.255	0.249	0.235	**0.998**	**0.25**		
Waste generation	0.245	0.250	0.270	0.254	**1.018**	**0.255**		
Sum	**1**	**1**	**1**	**1**	**4**	**1**		
Operation stage								
	Energy consumption	Carbon emissions	Potential for recyclable/ reusable materials	Waste generation	Indoor environmental quality	Water consumption	**Sum**	**Normalised weight**
Energy consumption	0.222	0.225	0.205	0.207	0.223	0.232	**1.314**	**0.219**
Carbon emissions	0.146	0.147	0.162	0.159	0.154	0.161	**0.929**	**0.155**
Potential for recyclable/ reusable materials	0.171	0.144	0.158	0.154	0.159	0.145	**0.931**	**0.155**
Waste generation	0.171	0.161	0.150	0.147	0.148	0.147	**0.924**	**0.154**
Indoor environmental quality	0.170	0.207	0.187	0.193	0.189	0.188	**1.134**	**0.189**
Water consumption	0.120	0.116	0.138	0.140	0.127	0.127	**0.768**	**0.128**
Sum	**1**	**1**	**1**	**1**	**1**	**1**	**6**	**1**
Social dimension								
Retrofitting stage								
	Noise impact on neighbourhood	Emission impact on neighbourhood	Safety of retrofitting construction	Impact on cultural heritage	Impact on surrounding traffic and pedestrians	Impact on relocating tenants	**Sum**	**Normalised weight**
Noise impact on neighbourhood	0.145	0.162	0.137	0.153	0.145	0.129	**0.871**	**0.145**
Emission impact on neighbourhood	0.159	0.178	0.159	0.198	0.200	0.187	**1.081**	**0.180**
Safety of retrofitting construction	0.240	0.254	0.227	0.203	0.205	0.234	**1.364**	**0.227**
Impact on cultural heritage	0.141	0.134	0.166	0.149	0.159	0.141	**0.890**	**0.148**
Impact on surrounding traffic and pedestrians	0.163	0.143	0.180	0.153	0.163	0.163	**0.975**	**0.163**
Impact on relocating tenants	0.152	0.129	0.131	0.144	0.128	0.136	**0.819**	**0.137**
Sum	**1**	**1**	**1**	**1**	**1**	**1**	**6**	**1**
Operation stage								
	Accessibility to building facilities for people with special needs	Accessibility to building services	Impacts on maintenance and maintainability from newly added building fabrics and building systems	Safety and security of users	Room flexibility for different demands	**Sum**	**Normalised weight**	
Accessibility to building	0.259	0.250	0.268	0.266	0.251	**1.295**	**0.259**	

facilities for people with special needs								
Accessibility to building services	0.174	0.167	0.162	0.171	0.158	**0.833**	**0.167**	
Impacts on maintenance and maintainability from newly added building fabrics and building systems	0.158	0.169	0.163	0.176	0.151	**0.817**	**0.163**	
Safety and security of users	0.216	0.216	0.205	0.221	0.252	**1.110**	**0.222**	
Room flexibility for different demands	0.194	0.198	0.202	0.165	0.187	**0.946**	**0.189**	
Sum	1	1	1	1	1	**5**	**1**	

Appendix E-1. Insulation performance

Table E1-1. Heat transfer coefficient of external walls and roofs

		Insulation materials	**Thickness(1) (mm)**	**Thermal conductivity(2) (W/m•K)**	**Heat transfer resistance(3) (m^2•K/W)**	**Heat transfer coefficient(4) (U value) (W/m^2•K)**
External walls (from interior to exterior) (standard value: U≤1.0 W/m^2•K)						
Before retrofitting		Cement mortar for internal finishes	20	0.93	0.022	2.029
		Solid clay brick	240	0.81	0.296	
		Cement mortar for fixing tiles to brick wall	20	0.93	0.022	
		Tiles on the external surface of walls	8	2.3	0.003	
After retrofitting	Remaining original walls	Cement mortar for internal finishes	20	0.93	0.022	0.692
		Solid clay brick	240	0.81	0.296	
		Cement mortar	20	0.93	0.022	
	Newly added insulation materials	Cement mortar with interface agent	10	0.8	0.013	
		EPS board	45	0.048	0.938	
		Alkali resistant fibreglass mesh	3	0.8	0.004	
		Waterproof paint	1.5	0.7	0.002	
Roofs (from top to bottom) (limit value: U≤0.7 W/m^2•K)						
Before retrofitting		Prefabricated insulation panel	60	1.74	0.034	3.356
		Concrete	40	1.74	0.023	
		Waterproof layer	2	/	/	
		Cement mortar	20	0.93	0.022	
		Structural plate	120	1.74	0.069	
After retrofitting	Newly added insulation materials	Concrete (30MPa with fine stone)	40	1.74	0.023	0.549
		Asphalt felt	1	/	/	
		Cement mortar	20	0.93	0.022	
		XPS board	50	0.033	1.515	
		SBS modified bituminous sheet materials	2	/	/	
	Remainedor iginal roofs	Concrete	40	1.74	0.023	
		Waterproof layer	2	/	/	
		Cement mortar	20	0.93	0.022	
		Structural plate	120	1.74	0.069	

Calculation:

(4)=1÷(sum of (3) +0.15)

(3)=1÷(2)×(1)÷1000

Note:

Thermal conductivity and thickness of each material is designed based on the local standard, Design Standard for Energy Efficiency of Public Buildings (DB33/1036-2007) (UAD, ZIAD & CMA 2007).

Table E1-2. Heat transfer coefficient of windows

	Window types	Heat transfer coefficient of the whole window ($W/m^2 \cdot K$)	Visible light transmittance	Shading coefficient of glazing(1)	Shading coefficient of external sun shading device(2) (SD_H)	Overall shading coefficient (SC)(3)
Limited Value		**• U≤4.7 for east- and north-facing windows** **• U≤3.5 for west- and south-facing windows**	/	/	/	**SC≤0.55**
Before retrofitting	Steel frame with single glazing (3mm)	5	0.83	1	/	/
	Plastic steel frame with single glazing (3mm)	6.6	0.83	1	/	/
After retrofitting	Aluminium frame with double glazing (5mm low-e+9mm air+5mm normal glazing)	2.57	≥0.72	0.62	0.72	0.446

Calculation:

(3)=(1)×(2)

Note:

The heat transfer coefficient of the whole window is adopted from the local standard, Design Standard for Energy Efficiency of Public Buildings (DB33/1036-2007) (UAD, ZIAD & CMA 2007).

Appendix E-2. Environmental impact assessment

Table E2-1. Materials and products used for the retrofitting of the case study building

Part of building	Retrofitting activity			Materials		Thickness (mm)	Specification of materials	Quantity	Unit	Total weight (kg)	Reference
External walls and roofs	A1	Install/upgrade insulation for external walls and roofs	External walls (Area of externall walls excluding windows and doors is about 12590.2m^2)	Cement mortar with interface agent (cement:sand = 1:3)		10	Weight ratio of cement and sand = 1:3 Density: about 2186 kg/m^3	275,223.60	kg	275,224	[1]
				EPS board		45	Area of one board: 1200mm*600mm Density: about 15.5kg/m^3	17,487.00	pieces	8,782	
				Alkali resistant fiberglass mesh		3	Density: about 160g/m^2	37.77	m3	2,014	
				Waterproof paint		1.5	Weight: 0.2kg/m^2 for one coat (double coats are needed)	18.89	m3	5,036	
			Roofs (Area of roofs is about 1300m^2)	Concrete (30MPa with fine stone) (Containing ø4@200 cold-drawn steel wire)	Steel mesh	40	Type: ø4@200 cold-drawn steel wire	1,500.00	kg	127,340	
					Concrete (C30)		Density: about 2420 kg/m^3	52.00	m3		
				Asphalt felt		1	Type: Label 200 Each roll weights about 15kg	65.00	rolls	975	
				Cement mortar (cement:sand = 1:3)		20	The weight ratio of cement and sand = 1:3 Density: about 2000 kg/m^3	52,000.00	kg	52,000	
				XPS board		50	Area of one board=1200mm*600mm Density: about 35kg/m^3	1,806.00	pieces	2,276	
				Styrene butadiene styrene(SBS) modified bituminous sheet materials		3	Area of each roll=10m^2 Weight: 35kg/roll	130.00	rolls	4,550	
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames (Area of windows = 2958.7m^2)		Glass		5	Type: 5mm low-e glazing + 9mm air + 5mm normal glazing Density: 2500 kg/m^3	29.59	m3	73,968	[1]
				Aluminium frames			Depth: 80mm Thickness:1.4mm For this type of frame, each window area needs about 8.2kg aluminum Area of each window: 1800mm*1800mm	913.00	frames	24,257	
	A3	Install aluminium sun shading slats for windows facing south		Aluminium sun shading slats			Area of each panel =900mm*1800mm Weight: 40kg/each	280.00	panels	11,200	[1,2]
Lighting	A4	Install motion sensors					Weight: 0.5kg/each	900.00	pieces	450	[3]
	A5	Change T8 fluorescent bulbs to T8 LED					Weight: 0.23/each	2,900.00	bulbs	667	[4]
Lifts	A6	Change existing lifts to energy efficient lifts					Type: REGEN-M Weight: 336kg Load capacity of each lift: 1000kg	4.00	lifts	1,344	[5]
Energy supply	A7	Install PV panels					Area of each panel: 1956mm*992mm Weight: 22.5kg/panel Electricity power: 300W/panel Efficiency rate is 75% Designed yearly electricity generation: about 20531.3kWh	50.00	panels	1,125	[6]
BMCS	A8	Install building energy consumption monitoring system						1.00		/	[7]
Water system	A9	Change existing taps and toilets to water-saving ones		Change existing water taps to water-saving taps			Type: hob mount infrared sensor taps Material: brass Weight: about 2kg/each Duration of each use: 30 seconds Pressure: 0.06 - 0.6 MPa Flow rate: 4.5L/minute	200.00	taps	400	[8]
				Change existing toilets to water-saving toilets with high pressure water tanks			Type: Siphonix toilet with dual flush tank Material: ceramics Weight: about 16kg/each Flow rate: 4.5L/flush	86.00	toilets	1,376	[9]
	A10	Install water treatment system for recycling greywater and rainwater		Above-ground box-type integrated water treatment plant			Type: HSHA/O Size of water tank: 3500mm*2200mm*1600mm Weight: 150 kg Power: 2.5kW Flow rate: 10m^3/hour Speed of treatment: 40m^3/hour Treatment rate: 60%	1.00	item	/	[10]

Note:

- Insulation for external walls, roofs, windows, and sun shading devices are designed based on the local standard (reference [1]).
- The selection of materials and products is in consultation with two local professionals in the construction sector.
- The specifications of required materials and products based on local suppliers are cited as below.

References

[1] SAMR & SAC 2020
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Table E2-2. Energy consumption and CO_2 emissions by operating construction equipment in the retrofitting stage

Part of building	Retrofitting activity			Equipment	Specification of equipment	Power(1) (kW)	Number(2)	Operation duration per equipment(3) (hours)	Amount of diesel needed per hour(4) (kg)	Energy consumption of each type of equipment(5) (MJ)	Energy consumption by each retrofitting activity(6) (MJ)	Carbon emissions by each type of equipment(7) (kg)	Carbon emissions by each retrofitting activity(8) (kg)
External walls and roofs	A1	Install/upgrade insulation for external walls and roofs	External walls	Electric suspended platform	Load capacity: 0.63 ton	2.5	8	480	/	34,560	65,201	7,776	14,670
				Rotary hammer		0.98	16	480	/	27,095		6,096	
				Mortar mixer	Volume: 200 L	2.5	2	197	/	3,546		798	
			Roofs	Rebar cutting machine		2.2	1	1.5	/	12	21,656	3	4,873
				Bar straightening machine		1.5	1	4.5	/	24		5	
				Tapered reverse tilting concrete mixer	Output capacity: 500 L	18.5	1	42	/	2,797		629	
				Mortar mixer	Volume: 200 L	2.5	1	42	/	378		85	
				Autocrane	Load capacity: 50 ton		1	64	6.5	17,762		3,996	
				Concrete pump truck	Pump capacity: 70 m^3/hour		1	2	8	683		154	
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames		Electric suspended platform	Load capacity: 0.63 ton	2.5	4	115	/	4,140	4,140	932	932
	A3	Aluminium sun shading slats for windows facing south		Autocrane	Load capacity: 50ton		2	51	6.5	28,307	42,823	6,369	9,635
				AC arc welder (32KVA)		12	2	168	/	14,515		3,266	
Lighting	A4	Install motion sensors		Mobile elevator	Load capacity: 300kg	1.5	2	225	/	2,430	2,430	547	547
	A5	Change T8 fluorescent bulbs to T8 LED		Mobile elevator	Load capacity: 300kg	1.5	2	363	/	3,920	3,920	882	882
Lifts	A6	Change existing lifts to energy efficient lifts		Electric winch	JK1.5T with Single drum Speed: 7-12m/minute	7.5	1	92	/	2,484	2,484	559	559
Energy supply	A7	Install PV panels		Autocrane (50ton)	Load capacity: 50 ton		1	24	6.5	6,661	21,176	1,499	4,765
				AC arc welder (32KVA)		12	2	168		14,515		3,266	
BMCS	A8	Install building energy consumption monitoring system		/	/	/	/	/	/	/	/	/	/
Water system	A9	Change existing taps and toilets to water-saving ones	Taps	/	/	/	/	/	/	/	/	/	/
			Toilets	/	/	/	/	/	/	/	/	/	/
	A10	Install water treatment system for recycling greywater and rainwater		Autocrane	Load capacity: 8 ton	/	1	4	3.6	615	635	138	143
				Electric single stage centrifugal water pump	Pump height: 100 m	3.7	1	1.5	/	20		4	

Calculation:

- For equipment whose energy source is electricity, energy consumption (5) = (1)×(2)×(3)×3.6
- For equipment whose energy source is diesel, energy consumption (5) = (2)×(3)×(4)×11.86×3.6

Where,

- 11.86 kWh/kg is the coefficient of converting diesel consumption to electricity consumption based on reference [1].
- 3.6 is coefficient for converting kWh to MJ

• Carbon emissions (7) = (5)÷3.6×0.81

Where,

- 0.81 kg CO_2/kWh is carbon intensity of electricity generation in Zhejiang Province, China according to reference [2]

References

[1] SAMR & SAC 2020

[2] Ding & Ying 2019

Table E2-3. Embodied energy and embodied carbon emissions in the retrofitting stage

Part of building	**Retrofitting activity**			**Materials**		**Amount$^{(1)}$**	**Unit**	**EE coefficient$^{(2)}$ (MJ/unit)**	**EC coefficient$^{(3)}$ (kg CO_2/unit)**	**EE(4) (MJ)**	**Total EE of each retrofitting activity (MJ)**	**EC emission$^{(5)}$ (kg CO_2)**	**Total EC emission of each retrofitting activity (kg CO2)**	**Reference of EE**	**Reference of EC emission**
External walls and roofs	A1	Install/upgrade insulation for external walls and roofs	External walls (Area of external walls excluding windows and doors is about 12590.2m^2)	Interface cement mortar (cement:sand = 1:3)		275,223.6	kg	1.33	0.21	366,047.39	1,205,186	57,246.51	104,351	[6]	[6]
				EPS board		566.58	m^3	1,329.6	46.34	753,324.77		26,255.32		[10]	[10]
				Alkali resistant fiberglass mesh		2,014.4	kg	28	1.35	56,403.20		2,719.44		[6]	[6]
				Waterproof paint		5,036.1	kg	5.84	3.6	29,410.82		18,129.96		[8, 13]	[12]
			Roofs (Area of roofs is about 1300m^2)	Concrete (Containing ø4@200 cold-drawn steel wire)	Steel mesh	1,500	kg	29	2.2	43,500	692,312	3,300	80,951	[5]	[4]
					Concrete (C30)	52	m^3	2,841	297	147,732		15,444		[15]	[4]
				Asphalt felt		975	kg	3	0.16	2,925		157.95		[5]	[5]
				Cement mortar (cement:sand = 1:3)		52,000	kg	1.33	0.21	69,160		10,816		[6]	[6]
				XPS board		65.02	m^3	3,022	669	196,490.44		43,498.38		[10]	[4]
				Styrene butadiene styrene(SBS) bituminous sheet		4,550	kg	51.1	1.7	232,505		7,735		[6, 7]	[1]
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames (Area of windows = 2958.7m^2)		Glass		73,967.5	kg	16	0.03	1,183,480	1,886,921	2,219.03	232,414	[5, 9, 13]	[15]
				Aluminium frames		24,256.58	kg	29	9.49	703,440.94		230,194.98		[6]	[14]
	A3	Install aluminium sun shading slats for windows facing south		Aluminium slats		11,200	kg	29	9.49	324,800	324,800	106,288.0	106,288	[6]	[14]
Lighting	A4	Install motion sensors				/	/	/	/	/	/	/	/	/	/
	A5	Change T8 fluorescent bulbs to T8 LED				2,900	tubes	43	2.4	124,700	124,700	6,960	6,960	[2]	[3]
Lifts	A6	Change existing lifts to energy efficient lifts				/	/	/	/	/	/	/	/	/	/
Energy supply	A7	Install PV panels				97.02	m^2	4,070	249	394,871.4	394,871	24,158	24,158	[6]	[11]
BMCS	A8	Install building energy consumption monitoring system				/	/	/	/	/	/	/	/	/	/
Water system	A9	Change existing taps and toilets to water-saving ones	Change to hob mount infrared sensor taps	Brass		2000	kg	20	1.12	40,000	40,000	2240	2240	[6]	[6]
			Change to siphonix toilet with dual flush tank	Ceramics		1290	kg	12.1	0.78	15,609	15,609	1006	1006	[7]	[14]
	A10	Install water treatment system for recycling greywater and rainwater		Above-ground box-type integrated water treatment plant		/	/	/	/	/	/	/	/	/	/

Calculation:

(4)=(1)×(2)

(5)=(1)×(3)

Where,

- Data of column (1) is the amount of building materials and service system, which can be found in Table A2-1

References

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[4] Cang et al. 2021
[5] Chen et al. 2022
[6] Hammond & Jones 2011
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[12] Wang 2009
[13] Yan 2011
[14] Zhang & Wang 2016
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Table E2-4. Operation energy consumption and CO_2 emissions

Building service system	Retrofitting activities		Electricity consumption and carbon eimssion before retrofitting				Potential electricity saving on the service system$^{(5)}$	Potential electricity saving on the whole building $^{(6)}$	Electricity consumption after retrofitting		Carbon emission after retrofitting		Reference
			% of the total electricity consumption/ carbon emission by the building service system$^{(1)}$	Amount of electricity consumption of the building service system		Amount of carbon emissions by the building service system$^{(4)}$ (kg CO_2)			Difference on annual electricity consumption by retrofitting activities$^{(7)}$ (MJ)	Annual electricity consumption by the service system after retrofitting $^{(8)}$ (MJ)	Difference on annual carbon emissions by retrofitting activities$^{(9)}$ (kg CO_2)	Annual carbon emission by the upgraded service system after retrofitting$^{(10)}$ (kg CO_2)	
				(kWh)$^{(2)}$	(MJ)$^{(3)}$								
HVAC	A1	Install/upgrade insulation for external walls and roofs	22%	403,977.64	1,454,319.50	402,765.66	60%	13.20%	-872,592	581,728	-196,333	206,433	[7, 10]
	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames					11.3%	2.49%	-164,338	1,289,981	-36,976	365,790	[12]
	A3	Aluminium sun shading slats for windows facing south					9%	1.98%	-130,889	271,877	-29,450	373,316	[11]
Lighting system	A4	Install motion sensors	40%	734,504.8	2,644,217.3	732,301.2	30%	12%	-793,265	1,850,952	-178,485	553,817	[9]
	A5	Change T8 fluorescent bulbs to equivalent T8 LED					/	/	-313,200	2,331,017	-70,470	661,831	[5]
Lifts	A6	Change existing lifts with energy efficient lifts	1%	18,362.62	66,105.43	18,307.53	30%	0.3%	-19,832	46,274	-4,462	13,845	[1, 2, 3, 8]
Energy supply	A7	Install PV panels	/	/	/	/	/	1.11%	-73,377	-73,377	-16,510	-16,510	[14]
BMCS	A8	Install building energy consumption monitoring system	/	/	/	/	/	2.4%	-158,653	-158,653	-35,697	-35,697	[4, 8]
Water system	A9	Change existing taps and toilets to water-saving ones	/	/	/	/	/	/	/	/	/	/	/
	A10	Install water treatment system for	/	/	/	/	/	/	6,750	6,750	1,519	1,519	[13]

Note: The negative symbol "-" represents energy saving or carbon emissions reduction

Calculation:

(1) Electricity consumption

- Difference on annual electricity consumption by retrofitting activity A1, A2, A3, A4, A6, A7 and A8 is calculated as:

(7)=(6)×1,836,262×3.6

(6)= (1)×(5)

Where,

- Data (5) are cited from below references.
- 1,836,262 kWh is the total annual energy consumption by the case building before retrofitting, shown in Table 7.1.
- Data of (1) are based on electricity bills of the building during the past three years, shown in Figure 8.1.

- For retrofitting activity A1, A2, A3, A4 and A6, difference on annual electricity consumption can also be calculated as:

(7)=(3)×(5)

(3)=(2)×3.6

(2)=(1)×1,836,262

Where,

- Data of (2) and (3) can be achieved by multiplying (1) with total annual energy consumption (or carbon emissions) of the case building before retrofitting, shown in Table 7.1.
- 3.6 is coefficient for converting kWh to MJ

- Difference on annual electricity saving by retrofitting activity A5 is calculated as:

(32-17)÷1000×2900×8×250×3.6=313,200 MJ

Where,

- 32W is the power of one T8 fluorescent bulb based on reference [5].
- 17W is the power of one T8 LED bulb based on reference [5].
- There are 2,900 bulbs that need to be replaced.
- Assuming a working day of 8 hours, and 250 working days per year.

- 3.6 is coefficient for converting kWh to MJ

- Annual electricity consumption by upgraded building service systems by retrofitting activity A1 – A8 is calculated as:

(8)=(3)+(7)

Where,

- (8) is the annual electricity consumption by the upgraded building service system after implementing the retrofitting activity
- (3) is the annual electricity consumption (in MJ) by the building service system before retrofitting
- (7) is the difference on the annual energy consumption of the building service system by the retrofitting activity

- Annual electricity consumption by retrofitting activity A10 is calculated as:

- The power of the above-ground box-type integrated water treatment plant is 2.5 kW, and treatment speed is 40 kL/hour based on reference [12].
- Based on the water bill during the past three years, annual water consumption is 23,970 kL (shown in Table 7.10).
- Assuming 250 working days per year, about 95.88 kL water is consumed per working day by the case building before retrofitting.
- Based on above information, the time that the water treatment plant works about 3 (≈95.88/40) hour maximum per working day.
- Therefore, the electricity consumption by operating the water treatment plant is: 2.5×3×250×3.6=6750 MJ.

(2) Carbon emissions

- Difference in annual carbon emissions by retrofitting activities is calculated as:

(9)=(7)÷3.6×0.81

Where,

- (7) is the difference on annual energy consumption of the building service system by the retrofitting activity
- 0.81 kg CO_2/kWh is carbon intensity of electricity generation in Zhejiang Province, China according to reference [6]

- Annual carbon emissions of building service systems after implementing the retrofitting activity are calculated as:

(10)=(4)+(9)

Where,

- (4) is annual carbon emissions of the building service system before retrofitting
- (9) is the difference on the annual carbon emissions of the building service system by the retrofitting activity

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Table E2-5. Recurrent embodied energy and recurrent carbon emissions in the operation stage

Part of building	**Retrofitting activity**			**Service life$^{(1)}$ (years)**	**EE$^{(2)}$ (MJ)**	**EC emission$^{(3)}$ (kg CO2)**	**Recurrent EE$^{(4)}$ (MJ)**	**Recurrent EC emission$^{(5)}$ (kg CO_2)**
External walls and roofs	A1	Install/upgrade insulation for external walls and roofs	External walls	20	1,205,186.18	104,351.23	2,410,372	208,702
			Roofs	20	692,312.44	80,951.33	1,384,625	161,903
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames		20	1,886,920.94	232,414.01	3,773,842	464,828
	A3	Install aluminium sun shading slats for windows facing south		30	324,800.00	106,288.00	324,800	106,288
Lighting	A5	Change T8 fluorescent bulbs to T8 LED		30	124,700.00	6,960.00	124,700	6,960
Energy supply	A7	Install PV panels		30	394,871.40	24,157.98	394,871	24,158
Water system	A9	Change existing taps and toilets to water-saving ones	Taps	50	40,000.00	2,240.00	/	/
			Toilets	20	15,609.00	1,006.20	31,218	2,012

Calculation:

(4)=(2)×integer of [the study period/(1)]

(5)=(3)×integer of [the study period/(1)]

Where,

- Data of (2) and (3) can be found in Table A2-3
- Assuming a 50-year remaining service life as the study period for this case study

Note:

Service life of building materials and service systems (in column (1)) can be found in Table 4.5 in Chapter 4, adopted from Australian Cost Management Manual, Volume 3; Kubba 2010; EATS 2015; Penny 2015; Kono et al. 2016; Alam et al. 2017; RICS 2018; and Tavares, Silva & de Brito 2020

Table E 2-6. Total energy consumption by retrofitting activities

Part of building	**Retrofitting activity**			**Retrofitting stage**			**Operation stage**			**Total difference on energy consumption by retrofitting activities$^{(7)}$ (MJ)**
				EE$^{(1)}$ (MJ)	**Energy consumption by operating construction equipment$^{(2)}$ (MJ)**	**Total consumption on retrofitting stage$^{(3)}$ (MJ)**	**Recurrent EE$^{(4)}$ (MJ)**	**Difference on energy consumption by retrofitting activities$^{(5)}$ (MJ)**	**Total difference on operation stage$^{(6)}$ (MJ)**	
External walls and roofs	A1	Install/upgrade insulation for external walls and roofs	External walls	1,205,186	65,201	1,984,356	2,410,372	-43,629,585	-39,834,588	-37,850,232
			Roofs	692,312	21,656		1,384,625			
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames		1,886,921	4,140	1,891,061	3,773,842	-8,216,905	-4,443,063	-2,552,002
	A3	Install aluminium sun shading slats for windows facing south		324,800	42,823	367,623	324,800	-6,544,438	-6,219,638	-5,852,015
Lighting	A4	Install motion sensors		/	2,430	2,430	/	-39,663,259	-39,663,259	-39,660,829
	A5	Change T8 fluorescent bulbs to T8 LED		124,700	3,920	128,620	124,700	-15,660,000	-15,535,300	-15,406,680
Lifts	A6	Change existing lifts to energy efficient lifts		/	2,484	2,484		-991,582	-991,582	-989,098
Energy supply	A7	Install PV panels		394,871	21,176	416,047	394,871	-3,668,852	-3,273,980	-2,857,933
BMCS	A8	Install building energy consumption monitoring system		/	/	/	/	-7,932,652	-7,932,652	-7,932,652
Water system	A9	Change existing taps and toilets to water-saving ones	Taps	40,000	/	55,609	/	/	31,218	86,827
			Toilets	15,609	/		31,218			
	A10	Install water treatment system for recycling greywater and rainwater		/	635	635	/	337,500	337,500	338,135

Note: symbol “-” represents energy saving by retrofitting activities

Calculation:

(3)=(1)+(2)

(6)=(4)+(5)

(7)=(3)+(6)

Where,

- Data in column (1) can be found in Table A2-3
- Data in column (2) can be found in Table A2-2
- Data in column (4) can be found in Table A2-5
- Data in column (5) is calculated as: (5)= the study period (50 years)×Column (6) in Table A2-4

Table E2-7. Total carbon emissions by retrofitting activities

Part of building	Retrofitting activity			Retrofitting stage			Operation stage			Total difference on carbon emissions by retrofitting activities(7) (kg)
				EC emissions(1) (kg)	Carbon emissions by operating construction equipment(2) (kg)	Total emissions on retrofitting stage(3) (kg)	REC emissions(4) (kg)	Difference on carbon emissions by retroiftting activities(5) (kg)	Total difference on operation stage(6) (kg)	
External walls and roofs	A1	Install/upgrade insulation for external walls and roofs	External walls	104,351	14,670	204,845	208,702	-9,816,657	-9,446,051	-9,241,206
			Roofs	80,951	4,873		161,903			
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames		232,414	932	233,346	464,828	-1,848,804	-1,383,976	-1,150,630
	A3	Install aluminium sun shading slats for windows facing south		106,288	9,635	115,923	106,288	-1,472,499	-1,366,211	-1,250,287
Lighting	A4	Install motion sensors		/	547	547	/	-8,924,234	-8,924,234	-8,923,687
	A5	Change T8 fluorescent bulbs to T8 LED		6,960	882	7,842	6,960	-3,523,500	-3,516,540	-3,508,698
Lifts	A6	Change existing lifts to energy efficient lifts		/	559	559	/	-223,106	-223,106	-222,547
Energy supply	A7	Install PV panels		24,158	4,765	28,923	24,158	-825,492	-801,334	-772,411
BMCS	A8	Install building energy consumption monitoring system		/	/	/	/	-1,784,847	-1,784,847	-1,784,847
Water system	A9	Change existing taps and toilets to water-saving ones	Taps	2,240	/	3,246	/	/	2,012	5,259
			Toilets	1,006	/		2,012			
	A10	Install water treatment system for recycling greywater and rainwater		/	143	143	/	75,938	75,938	76,080

Note: symbol "-" represents reduction of carbon emission by retrofitting activities

Calculation:

(3)=(1)+(2)

(6)=(4)+(5)

(7)=(3)+(6)

Where,

- Data in column (1) can be found in Table A2-3
- Data in column (2) can be found in Table A2-2
- Data in column (4) can be found in Table A2-5
- Data in column (5) can be calculated as: (5)= the study period (50 years)×Column (8) in Table A2-4

Table E2-8. Use of recyclable/reusable materials

Part of building	Retrofitting activity			Materials		Weight(1) (kg)	Total weight added by a retrofitting activity(2) (kg)	Recyclable or reusable materials	Recyclable or reusable rate(3) (%)	Weight of reusable or recyclable materials(4) (kg)	% of recyclable or reusable materials(5)	Note
External walls and roofs	A1	Install/upgrade insulation for building envelops	External walls	Mortar (cement:sand = 1:3)		275,223.6	478,196.64	• Steel • Concrete	/	127,340	27%	/
				EPS board		8,781.97						
				Alkali resistant fiberglass mesh		2,014.43						
				Waterproof paint		5,036.08						
			Roofs	Concrete	Steel wire	1,500						
					Concrete (C30)	125,840						
				Asphalt felt		975						
				Mortar (cement:sand = 1:3)		52,000						
				XPS board		2,275.56						
				Styrene butadiene styrene (SBS) bituminous sheet		4,550						
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frames		Glass		73,967.5	98,224.08	• Glass • Aluminium	/	98,224.08	100%	/
				Aluminium frames		24,256.58						
	A3	Install aluminium sun shading slats for windows facing south		Aluminium sun shading slats		11,200	11,200	• Aluminium	/	11,200	100%	/
Lighting	A4	Install motion sensors				450	450	/	/	0	0%	/
	A5	Change T8 fluorescent bulbs to equivalent T8 LED		LED bulbs		667	667	• Glass	20%	133	20%	[1]
Lifts	A6	Change existing lifts to energy efficient lifts		Lifts		1,344	1,344	Whole lifts	90%	1,210	90%	[2]
Energy supply	A7	Install PV panels				1,125	1,125	/	/	0	0%	/
BMCS	A8	Install energy consumption monitoring system				/	/	/	/	0	0%	[3]
Water system	A9	Change existing taps and toilets to water-saving ones	Taps	Brass		400	1,776	• Brass • Ceramics	/	1,776	100%	/
			Toilets	Ceramics		1,376						
	A10	Install water treatment system for recycling greywater and rainwater		Above-ground box-type integrated water treatment plant		150	150	Whole treatment plant	90%	135	90%	[4]

Note: highlighted materials are recyclable or reusable materials

Calculation:

- For retrofitting activities A1, A2, A3, A4, A7 and A9, the proportion of recyclable or reusable materials for future use is calculated as:

(5)=(4)÷(2)×100%

Where,

- (4) is sum of the weight of recyclable or reusable materials from column (1) (the highlighted items)
- (2) is sum of (1) contained in the retrofitting activity
- Data of (1) can be found in Table A2-1

- For retrofitting activities A5 and A6, proportion of recyclable or reusable materials for future use is calculated as:

(5)=(3)×(2)

Where,

- (3) is reuse or recycle rate, referring to below notes
- (2) is sum of (1) contained in the retrofitting activity
- Data of (1) can be found in Table A2-1

Note:

[1] Based on the study by Franz and Wenzi (2017), about 20% of the weight of a LED bulb can be recycled. This figure is adopted in this case study as the recyclable rate of retrofitting activity A5.

[2] Removed lifts are often disassembled, and most components can be recycled or reused. Considering the finishing and lights in lift cars, it is assumed that 90% of removed lifts can be recycled or reused.

[3] There is no data about weight or recycling or reuse information available for the building energy consumption monitoring system. The main components of the monitoring system are electricity meters, which are very light compared to other added building materials or service system. Therefore, it is neglected in this estimation.

[4] Similar to lifts, most components of the water treatment plant can be recycled or reused. Assuming 10% of a removed water treatment plant is broken and will go to disposal, 90% of the water treatment plant can be recycled or reused.

Table E2-9. Waste generation

Part of building	**Retrofitting activity**			**Service life(1) (years)**	**Total weight added by a retrofitting activity(2) (kg)**	**Weight of recyclable or reusable materials(3) (kg)**	**Total waste generation(4) (kg)**
External walls and	A1	Install/upgrade insulation for external walls and roofs	External walls	20	478,197	127,340	701,713
			Roofs	20			
Windows	A2	Change existing single-glazing windows to low-e double glazing with aluminium frame		20	98,224	98,224.08	0
	A3	Install aluminium sun shading slats for windows facing south		30	112,200	112,200	0
Lighting	A4	Install motion sensors		15	450	0	1,350
	A5	Change T8 fluorescent bulbs to T8 LED		30	667	133	534
Lifts	A6	Change existing lifts to energy efficient lifts		30	1,344	1,210	134
Energy supply	A7	Install PV panels		30	1,125	0	1,125
BMCS	A8	Install building energy consumption monitoring system		15	0	0	0
Water system	A9	Change existing taps and toilets to water-saving ones	Taps	50	400	400	0
			Toilets	20	1,376	1,376	0
	A10	Install water treatment system for recycling greywater and rainwater		30	150	135	15

Calculation:

(4)=[(2)-(3)]×integer of [the study period/(1)]

Where,

- (2) is the total weight of added materials by retrofitting activities, which can be found in Table A2-1
- (3) is weight of recyclable or reusable materials, which can be found in Table A2-8
- Assuming a 50-year remaining service life as the study period for this case study

Note:

Service life of building materials and service systems (in column (1)) can be found in Table 4.5 in Chapter 4, adopted from Australian Cost Management Manual, Volume 3; Kubba 2010; EATS 2015; Penny 2015; Kono et al. 2016; Alam et al. 2017; RICS 2018; and Tavares, Silva & de Brito 2020

Appendix E-3. Economic performance assessment

Table E3-1. EAC of building service system after implementing proposed retrofitting activities

Building service system	Retrofitting activities			Life expectancy	Retrofitting stage	Operation stage												EAC of the upgraded building service system after implementing the retrofitting activity(8)	Reference of initial cost
					Initial cost(1)	Annual electricity consumption by building service system after retrofitting		Annual water consumption by building service system after retrofitting(4)	Unit price of electricity/ water(5)	Annual operation cost(6)	Replacement cost(7) (¥)								
				years	¥	MJ(2)	kWh(3)	kL	¥/kWh or ¥/kL	¥	year 15	year 20	year 25	year 30	year 35	year 40	year 45	¥	
HVAC	A1	Add insulation for external walls and roofs	External walls	20	438,340	581,728	161,591	/	0.64	103,418.28		771,376				771,376		155,680	[1]
			Roofs	20	333,036														
	A2	Change single-glazing windows to low-e double glazing with aluminium frames		20	710,088	1,289,981	358,328	/	0.64	229,330.03		710,088				710,088		302,500	[2]
	A3	Install aluminium sun shading slats for windows facing south		30	249,480	271,877	75,521		0.64	48,333.67				249,480				108,405	[3]
Lighting system	A4	Install motion sensors		15	70,200	1,850,952	514,153	/	0.64	329,058.15	70,200			70,200			70,200	337,355	[4]
	A5	Change T8 fluorescent bulbs to T8 LED		30	83,810	2,331,017	647,505	/	0.64	414,403.07				83,810				421,935	[5]
Lifts	A6	Change existing lifts to energy efficient lifts		30	2,625,390	46,274	12,854	/	0.64	8,226.45				2,625,390				244,160	[6]
Energy	A7	Install PV panels		30	34,900	-73,377	-20,383	/	0.64	-13,044.81				34,900				-9908	[7]
BMCS	A8	Install building energy consumption monitoring system		15	270,000	-158,653	-44,070	/	0.64	-28,204.98	270,000			270,000			270,000	3,708	[8]
Water system	A9	Change existing taps and toilets to waer-saving ones	Taps	50	11,000	/	/	2,734	0.49	1,339.54		47,300				47,300		7,113	[9, 10]
			Toilets	20	47,300														
	A10	Install water treatmet system for recycling greywater and rainwater		30	31,900	6,750	1,875	-1,361	0.64 or 0.49	533.11				31,900				3,400	[11]

Note: The negative symbol “-” represents cost saving.

Calculation:

- Calculate operation cost: (6)=(3)×(5)

(3)=(2)÷3.6

Where,

- (2) can be found in column (8) in Table A2-4.

- For retrofitting activity A10, the operation of the water treatment system consumes electricity and results in water saving. Therefore, the annual cost of the water system by implementing retrofitting activity A10 is the annual electricity cost with compensation of cost saving by annual reduced water consumption.

- Calculation EAC of upgraded building service system:
  Step 1. Convert replacement cost (column (7) to NPV based on equation:

$$NPV = \frac{C}{(1+i)^d}$$

Where,

- C is replacement cost occurs at year d
- i is current real discount rate, 8% in this study

Step 2. Convert initial cost (1) and NPV of replacement cost (from step 1) to EAC based on equation:

$$EAC_{(1,7)} = \frac{P \times i \times (1+i)^n}{(1+i)^n - 1}$$

Where,

- $EAC_{(1,7)}$ is the EAC when only considering initial cost and replacement cost
- P is sum of initial cost (column (1)) and NPV of replacement cost from step 1
- n is the study period, 50 years

Step 3. Calculate total EAC (column (8)) of the upgraded building service system by a retrofitting activity:

(8)=$EAC_{(1,7)}$+(6)

Note:

- The life expectancy of building components and service systems is adopted from Australian Cost Management Manual, Volume 3 (2000), and studies by Kubba (2010), EATS (2015), Penny (2015), Kono et al. (2016), Alam et al. (2017), RICS (2018), and Tavares, Silva and de Brito 2020.
- According to CEIC database (CEIC 2022a), the electricity price for business use in China in 2022 is ¥0.64/kWh.
- According to CEIC database (CEIC 2022b), the water price for business use in China in 2022 is ¥ 0.49/kL.
- The initial cost of retrofitting activity A1 is adopted from the study about retrofitting by Chow, Li and Darkwa (2013), which is conducted in the same region and climate zone as this case study. For the capital cost of other building components and service systems, they are adopted from local procurement websites (accessed in 2022). The URLs are listed in the below references.

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[9] https://b2b.baidu.com/land?url=https%3A%2F%2Fb2bwork.baidu.com%2Fland%3Flid%3D1735054231525472959&query=节水水龙头&lattr=&xzhid=40649129&pi=b2b.s.main.9..5414118005152788&category=建材家装%3B水龙头%3B感应龙头&fid=67174400%2C1661959827567&iid=6af775f890a8412191db555aab7065f4&miniId=8469&jid=2403942115&prod_type=0
[10] https://b2b.baidu.com/land?url=http%3A%2F%2Fwww.51sole.com%2Ftp%2F337584751.htm&query=商用节水马桶&lattr=&xzhid=37326029&pi=b2b.s.main.7..0779386989916883&category=建材家装%3B卫浴洁具%3B普通坐便器&fid=67174400%2C1661959827567&iid=f644c437ac88500d9becd0ed93ef1e7e&miniId=8469&jid=1649070388&prod_type=0
[11] https://b2b.baidu.com/land?url=https%3A%2F%2Fwww.china.cn%2Fwushuichulichengtsb%2F5032117108.html&query=一体式水处理系统&lattr=ot&xzhid=35501229&pi=b2b.s.main.5..6263857252096584&category=机械工业%3B污水处理设备%3B污水处理成套设备&fid=67174400%2C1661958457006&iid=1b8cf047a5f3e65a6baf33c4fae02791&miniId=8469&jid=151168900&prod_type

Table E3-2. Equivalent annual cost or saving by retrofitting activities

Retrofitting activities			Life expectancy	Retrofitting stage	Operation stage												NPV of initial cost and replacement cost(8) (¥)	Equivalent annual cost or saving by retrofitting activities(9)
				Initial cost(1)	Difference on annual electricity consumption by retrofitting activities		Difference on water consumption by retrofitting activities(4)	Unit price of electricity/ water(5)	Difference on annual electricity/water cost by retrofitting activity(6)	Replacement cost(7) (¥)								
			years	¥	MJ(2)	kWh(3)	kL	¥/kWh or ¥/kL	¥	at year 15	at year 20	at year 25	at year 30	at year 35	at year 40	at year 45	¥	¥
A1	Add insulation for external walls and roofs	External walls	20	438,340	-872,591.7	-242,387	/	0.64	-155,127.41		771,376				771,376		972,380	-75,642
		Roofs	20	333,036														
A2	Change single-glazing windows to low-e double glazing with aluminium frames		20	710,088	-164,338.1	-45,649	/	0.64	-29,215.66		710,088				710,088		895,122	43,954
A3	Install aluminium sun shading slats for windows facing south		30	249,480	-130,888.76	-36,358	/	0.64	-23,269.11				249,480				274,273	-849
A4	Install motion sensors		15	70,200	-661,054.32	-183,626	/	0.64	-117,520.77	70,200			70,200			70,200	101,505	-109,223
A5	Change T8 fluorescent bulbs to T8 LED		30	83,810	-313,200	-87,000	/	0.64	-55,680.00				83,810				92,139	-48,148
A6	Change existing lifts to energy efficient lifts		30	2,625,390	-19,831.63	-5,509	/	0.64	-3,525.62				2,625,390				2,886,294	232,408
A7	Install PV panels		30	34,900	-73,377.03	-20,383	/	0.64	-13,044.81				34,900				38,368	-9,908
A8	Install building energy consumption monitoring system		15	270,000	-158,653.04	-44,070	/	0.64	-28,204.98	270,000			270,000			270,000	390,406	3,708
A9	Change existing taps and toilets to waer-saving ones	Taps	50	11,000	/	/	-1,233.75	0.49	-604.54		47,300				47,300		70,625	5,169
		Toilets	20	47,300														
A10	Install water treatment system for recycling greywater and rainwater		30	31,900	6,750	1,875	-1,361	0.49	533.11				31,900				35,070	3,400

Note: The negative symbol “-” represents cost saving.

Calculation:

(3)=(2)÷3.6

Where,

- (2) can be found in column (7) in Table A2-4

(6)=(3) (and/or (4))×(5)

$(8)=(1)+\sum[(7)\div(1+i)^{d}]$

Where,

- (1) can be found in column (1) in Table A3-1
- i is the current real discount rate, 8%
- d is the year that replacement cost occurs

$(9)=(6)+(8)\times i\times(1+i)^{n}\div[(1+i)^{n}-1]$

Where,

- n is study period in the case study, 50 years

Appendix E-4. Social performance assessment

Table E4-1. Social performance assessment

Life stage	Assessment criteria		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Retrofitting stage	Noise impact on neighbourhood	Professional 1	4	3	4	1	1	1	2	1	1	3
		Professional 2	2	4	3	1	1	1	3	2	1	1
		Professional 3	4	4	4	1	1	1	3	2	1	3
		Professional 4	4	3	3	1	1	1	4	3	1	2
		Professional 5	4	5	4	1	1	1	3	2	1	3
		Final score (average)	3.6	3.8	3.6	1	1	1	3	2	1	2.4
	Emission impact on neighbourhood	Professional 1	5	2	4	1	1	1	3	1	1	3
		Professional 2	3	3	3	1	1	1	2	1	1	2
		Professional 3	4	3	4	1	1	1	3	2	1	3
		Professional 4	4	2	3	1	1	1	3	2	1	2
		Professional 5	3	3	3	1	1	1	3	2	1	3
		Final score (average)	3.8	2.6	3.4	1	1	1	2.8	1.6	1	2.6
	Impacts on safety of undertaking the retrofitting activity	Professional 1	4	4	4	2	3	3	4	3	2	2
		Professional 2	3	3	4	1	2	1	3	1	2	1
		Professional 3	4	3	4	1	3	3	3	2	2	2
		Professional 4	4	4	4	2	3	2	3	2	1	2
		Professional 5	3	4	3	2	2	2	3	2	1	2
		Final score (average)	3.6	3.6	3.8	1.6	2.6	2.2	3.2	2	1.6	1.8

	Impacts on cultural heritage	Professional 1	4	4	4	1	1	1	3	1	2	3
		Professional 2	4	4	3	1	2	2	3	2	1	4
		Professional 3	5	4	4	1	1	2	4	3	4	4
		Professional 4	2	3	5	2	2	2	5	3	3	3
		Professional 5	4	4	4	2	2	3	4	3	3	4
		Final score (average)	3.8	3.8	4	1.4	1.6	2	3.8	2.4	2.6	3.6
	Impacts on surrounding traffic and pedestrians	Professional 1	5	3	3	1	1	1	2	3	1	2
		Professional 2	4	4	3	1	1	2	3	1	1	1
		Professional 3	4	4	4	1	1	1	2	2	1	3
		Professional 4	4	3	3	1	1	1	2	2	2	3
		Professional 5	4	3	4	1	1	2	1	3	1	3
		Final score (average)	4.2	3.4	3.4	1	1	1.4	2	2.2	1.2	2.4
	Impacts on relocating tenants	Professional 1	2	3	2	2	4	4	1	1	4	2
		Professional 2	4	4	3	3	3	3	1	2	4	1
		Professional 3	4	4	3	3	3	3	2	2	3	1
		Professional 4	3	3	3	2	4	3	2	2	3	1
		Professional 5	4	4	3	1	3	3	2	2	4	1
		Final score (average)	3.4	3.6	2.8	2.2	3.4	3.2	1.6	1.8	3.6	1.2
Operation stage	Accessibility to building facilities for people with additional needs	Professional 1	2	2	2	3	2	3	2	2	4	2
		Professional 2	4	2	3	4	3	5	3	3	5	2
		Professional 3	3	3	3	3	2	4	3	3	4	2
		Professional 4	4	2	4	3	4	5	4	2	4	3
		Professional 5	4	3	4	3	4	5	4	3	4	3

		Final score (average)	3.4	2.4	3.2	3.2	3	4.4	3.2	2.6	4.2	2.4
	Accessibility to building services	Professional 1	5	3	5	2	2	3	2	2	4	2
		Professional 2	4	3	4	2	5	4	3	3	5	5
		Professional 3	4	4	4	3	3	4	3	2	4	3
		Professional 4	5	4	5	2	4	5	4	4	5	4
		Professional 5	4	4	4	2	4	4	4	3	4	3
		Final score (average)	4.4	3.6	4.4	2.2	3.6	4	3.2	2.8	4.4	3.4
	Impacts on maintenance and maintainability from newly added building components and service systems	Professional 1	4	2	2	2	3	4	2	5	3	2
		Professional 2	2	2	3	2	4	3	2	4	3	3
		Professional 3	3	2	3	2	3	4	2	3	4	2
		Professional 4	4	2	3	2	4	4	3	3	4	3
		Professional 5	4	2	2	2	4	3	2	2	4	2
		Final score (average)	3.4	2	2.6	2	3.6	3.6	2.2	3.4	3.6	2.4
	Impacts on safety and security of users	Professional 1	4	3	2	2	2	4	2	2	2	2
		Professional 2	2	4	1	2	2	4	3	2	4	2
		Professional 3	4	4	2	2	3	5	3	3	3	3
		Professional 4	4	4	2	2	4	4	3	3	4	3
		Professional 5	5	4	2	2	3	4	3	3	3	3
		Final score (average)	3.8	3.8	1.8	2	2.8	4.2	2.8	2.6	3.2	2.6
	Impacts on room flexibility for different demands	Professional 1	2	2	2	2	2	2	2	2	2	2
		Professional 2	3	2	4	2	2	2	2	2	4	3
		Professional 3	2	3	3	2	3	2	2	3	2	2

		Professional 4	3	2	2	2	3	2	2	3	2	2
		Professional 5	3	2	3	2	3	3	2	3	2	2
		Final score (average)	2.6	2.2	2.8	2	2.6	2.2	2	2.6	2.4	2.2

Note:

- The final score regarding each assessment criterion is the average score of the given scores by the five professionals, which can be calculated based on the Equation:

$$S_{ij} = \frac{\sum S_{ij}^{n}}{5}$$

Where,

S_{ij} – social assessment score of retrofitting activity i regarding assessment criterion j

S_{ij}^{n} – the rating score of retrofitting activity i regarding assessment criterion j given by the nth professional

- The rating scores are given based on the provided rating scale as the below table shows:

Impact range on retrofitting stage	**Value score**	**Performance range in operation stage**
Very significant impact	5	Excellent performance
Significant impact	4	Very good performance
Average impact	3	Good performance
Minor impact	2	Same as current performance
Minimum impact	1	Unsatisfied performance

Appendix E-5. Normalisation

Table E5-1. Normalising the estimation of environmental performance

Assessment criteria		Unit	Max	Min	Retrofitting activities																			
					A1		A2		A3		A4		A5		A6		A7		A8		A9		A10	
					Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.
Retrofitting stage	Energy consumption	MJ	1,984,355	0	1,984,355	0	1,891,061	5	367,623	81	2,430	100	128,620	94	2,484	100	416,047	79	0	100	55,609	97	635	100
	Carbon emission	kg CO_2	233,345	0	204,845	12	233,345	0	115,923	50	547	100	7,842	97	559	100	28,923	88	0	100	3,246	99	143	100
	Potential for reusable/recyclable materials	%	100%	0%	27%	27	100%	100	100%	100	0%	0	20%	20	90%	90	0%	0	0%	0	100%	100	90%	90
Operation stage	Potential savings on energy consumption	MJ	337500	-39,834,588	-39,834,588	100	-4,443,063	12	-6,219,638	16	-39,663,259	100	-15,535,300	40	-991,582	3	-3,273,980	9	-7,932,652	21	31,218	1	337,500	0
	Potential savings on carbon emission	kg CO_2	75938	-9,446,051	-9,446,051	100	-1,383,976	15	-1,366,211	15	-8,924,234	95	-3,516,540	38	-223,106	3	-801,334	9	-1,784,847	20	2,012	1	75,938	0
	Poential savings on water consumption	kL	0	-68,050	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-61,688	91	-68,050	100
	Waste generation	kg	701,731	0	701,731	0	0	100	0	100	1,350	100	534	100	134	100	1,125	100	0	100	0	100	15	100
	Potential for reusable/ recyclable materials	%	100%	0%	27%	27	100%	100	100%	100	0%	0	20%	20	90%	90	0%	0	0%	0	100%	100	90%	90

Note:

- The negative symbol "-" represents energy saving, carbon emissions, or water saving.
- Est. = Estimation; Norm. = Normalised score
- For impacts measured in positive direction, including use of reusable/recyclable materials in the retrofitting stage and operation stage, Equation 6.5 (in Chapter 6, ($N_{ij} = \frac{x_{ij}-x_{minj}}{x_{maxj}-x_{minj}}$) is used to normalise the estimation. Two decimals are saved in normalisation results, and to have a clear and concise expression, the normalisation results are multiplied by 100 to make them integer. It is done for other normalisations.
- For impacts measured in negative direction, including energy consumption and carbon emissions in the retrofitting stage, difference in energy consumption, difference in carbon emissions, difference in water consumption, and waste generation in the operation stage, Equation 6.6 (in Chapter 6, $N_{ij} = \frac{x_{max}-x_{ij}}{x_{maxj}-x_{minj}}$) is used to normalise the estimation.

Table E5-2. Normalising the estimation of economic performance

Retrofitting activities		EAC	
		Estimation (¥)	**Normalised score**
A1	Install/upgrade insulation for external walls and roofs	-75,642	84
A2	Change single-glazing windows to low-e double glazing with aluminium frames	43,954	52
A3	Install aluminium sun shading slats for windows facing south	-849	64
A4	Install motion sensors to lighting system	-132,728	100
A5	Change T8 fluorescent bulbs to T8 LED	-48,148	77
A6	Change existing lifts to energy efficient lifts	232,408	0
A7	Install PV panels	-9,908	66
A8	Install energy consumption monitoring system	3,708	63
A9	Change existing taps and toilets to water-saving ones	5,169	62
A10	Install water treatment system to recycle greywater and stormwater	3,400	63

Note:

- The negative symbol “-” represents cost saving.
- The maximum estimation is ¥232,408 by retrofitting activity A6, and the minimum estimation is -¥ 132,728 by retrofitting activity A4.
- Since the measure direction is negative, the equation $N_{ij} = \frac{x_{ij} - x_{minj}}{x_{maxj} - x_{minj}} \times 100$ is used to normalise equivalent annual cost or saving by the proposed retrofitting activities.

Table E5-3. Normalising the estimation of social performance

Social assessment criteria		Max	Min	A1		A2		A3		A4		A5		A6		A7		A8		A9		A10	
				Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.	Est.	Norm.
Retrofitting stage	Noise impact on neighbourhood	3.80	1.00	3.60	7	3.80	0	3.60	7	1.00	100	1.00	100	1.00	100	3.00	29	2.00	64	1.00	100	2.40	50
	Emission impact on neighbourhood	3.80	1.00	3.80	0	2.60	43	3.40	14	1.00	100	1.00	100	1.00	100	2.80	36	1.60	79	1.00	100	2.60	43
	Impacts on safety of undertaking the	3.80	1.60	3.60	9	3.60	9	3.80	0	1.60	100	2.60	55	2.20	73	3.20	27	2.00	82	1.60	100	1.80	91
	Impacts on cultural heritage	4.00	1.40	3.80	8	3.80	8	4.00	0	1.40	100	1.60	92	2.00	77	3.80	8	2.40	62	2.60	54	3.60	15
	Impacts on surrounding traffic and pedestrians	4.20	1.00	4.20	0	3.40	25	3.40	25	1.00	100	1.00	100	1.40	88	2.00	69	2.20	63	1.20	94	2.40	56
	Impacts on relocating tenants	3.60	1.20	3.40	8	3.60	0	2.80	33	2.20	58	3.40	8	3.20	17	1.60	83	1.80	75	3.60	0	1.20	100
Operation stage	Accessibility to building facilities for people with additional needs	4.40	2.40	3.40	50	2.40	0	3.20	40	3.20	40	3.00	30	4.40	100	3.20	40	2.60	10	4.20	90	2.40	0
	Accessibility to building services	4.40	2.20	4.40	100	3.60	64	4.40	100	2.20	0	3.60	64	4.00	82	3.20	45	2.80	27	4.40	100	3.40	55
	Impacts on maintenance and maintainability from newly added building component or building system	3.60	2.00	3.40	88	2.00	0	2.60	38	2.00	0	3.60	100	3.60	100	2.20	13	3.40	88	3.60	100	2.40	25
	Impacts on safety and security of tenants	4.20	1.80	3.80	83	3.80	83	1.80	0	2.00	8	2.80	42	4.20	100	2.80	42	2.60	33	3.20	58	2.60	33
	Impacts on room flexibility for different demands	2.80	2.00	2.60	75	2.20	25	2.80	100	2.00	0	2.60	75	2.20	25	2.00	0	2.60	75	2.40	50	2.20	25

Note:

- Est. = Estimation; Norm. = Normalised score
- For assessment criteria of the retrofitting stage, the measure direction is negative, the equation $N_{ij} = \frac{x_{ij}-x_{minj}}{x_{maxj}-x_{minj}} \times 100$ is used to normalise the estimations.
- For assessment criteria of the operation stage, the measure direction is positive, the equation $N_{ij} = \frac{x_{max}-x_{ij}}{x_{maxj}-x_{minj}} \times 100$ is used to normalise the estimations.

Table E5-4. Weighted environmental and social scores

Pillars	Life stage	Assessment criteria	Weight$^{(1)}$	Retrofitting activity																			
				A1		A2		A3		A4		A5		A6		A7		A8		A9		A10	
				Norm.$^{(2)}$	Weig.$^{(3)}$	Norm.$^{(2)}$	Weig.$^{(3)}$	Norm.$^{(2)}$	Weig.$^{(3)}$	Norm.$^{(2)}$	Weig.$^{(3)}$	Norm.$^{(2)}$	Weig.$^{(3)}$	Norm.$^{(2)}$	Weig.$^{(3)}$	Norm.$^{(2)}$	Weig.$^{(3)}$	Norm.$^{(2)}$	Weig.$^{(3)}$	Norm.$^{(2)}$	Weig.$^{(3)}$	Norm.$^{(2)}$	Weig.$^{(3)}$
Environmental dimension	**Retrofitting stage**	Energy consumption	**0.250**	0	0.00	5	1.18	81	20.37	100	24.97	94	23.38	100	24.97	79	19.76	100	25.00	97	24.30	100	24.99
		Carbon emissions	**0.245**	12	2.99	0	0.00	50	12.33	100	24.44	97	23.68	100	24.44	88	21.46	100	24.50	99	24.16	100	24.50
		Potential for reusable/recyclable materials	**0.250**	27	6.75	100	25.00	100	25.00	0	0.00	20	5.00	90	22.50	0	0.00	0	0.00	100	25.00	90	22.50
	Operation stage	Potential savings on energy consumption	**0.219**	100	21.90	12	2.61	16	3.57	100	21.81	40	8.65	3	0.72	9	1.97	21	4.51	1	0.17	0	0.00
		Potential savings on carbon emissions	**0.155**	100	15.50	15	2.33	15	2.33	95	14.73	38	5.89	3	0.49	9	1.40	20	3.10	1	0.12	0	0.00
		Potential savings on water consumption	**0.128**	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	91	11.65	100	12.80
		Waste generation	**0.154**	0	0.00	100	15.40	100	15.40	100	15.37	100	15.39	100	15.40	100	15.38	100	15.40	100	15.40	100	15.40
		Potential for reusable/recyclable materials	**0.155**	27	4.19	100	15.50	100	15.50	0	0.00	20	3.10	90	13.95	0	0.00	0	0.00	100	15.50	90	13.95
	Total weighted environmental score$^{(4)}$			**51.33**		**62.01**		**94.50**		**101.31**		**85.09**		**102.47**		**59.96**		**72.51**		**116.29**		**114.14**	
Social dimension	**Retrofitting stage**	Noise impact on neighbourhood	**0.145**	7	1.04	0	0.00	7	1.04	100	14.50	100	14.50	100	14.50	29	4.14	64	9.32	100	14.50	50	7.25
		Emission impact on neighbourhood	**0.180**	0	0.00	43	7.71	14	2.57	100	18.00	100	18.00	100	18.00	36	6.43	79	14.14	100	18.00	43	7.71
		Safety of retrofitting construction	**0.227**	9	2.06	9	2.06	0	0.00	100	22.70	55	12.38	73	16.51	27	6.19	82	18.57	100	22.70	91	20.64
		Impacts on cultural heritage	**0.148**	8	1.14	8	1.14	0	0.00	100	14.80	92	13.66	77	11.38	8	1.14	62	9.11	54	7.97	15	2.28
		Impacts on surrounding traffic and pedestrians	**0.163**	0	0.00	25	4.08	25	4.08	100	16.30	100	16.30	88	14.26	69	11.21	63	10.19	94	15.28	56	9.17
		Impacts on relocating tenants	**0.137**	8	1.14	0	0.00	33	4.57	58	7.99	8	1.14	17	2.28	83	11.42	75	10.28	0	0.00	100	13.70
	Operation stage	Accessibility to building facilities for people with additional needs	**0.259**	50	12.95	0	0.00	40	10.36	40	10.36	30	7.77	100	25.90	40	10.36	10	2.59	90	23.31	0	0.00
		Accessibility to building services	**0.167**	100	16.70	64	10.63	100	16.70	0	0.00	64	10.63	82	13.66	45	7.59	27	4.55	100	16.70	55	9.11
		Impacts on maintenance and maintainability from newly added building component or building system	**0.163**	88	14.26	0	0.00	38	6.11	0	0.00	100	16.30	100	16.30	13	2.04	88	14.26	100	16.30	25	4.08
		Impacts on safety and security of	**0.222**	83	18.50	83	18.50	0	0.00	8	1.85	42	9.25	100	22.20	42	9.25	33	7.40	58	12.95	33	7.40
		Impacts on room flexibility for different demands	**0.189**	75	14.18	25	4.73	100	18.90	0	0.00	75	14.18	25	4.73	0	0.00	75	14.18	50	9.45	25	4.73
	Total weighted social score$^{(4)}$			**81.97**		**48.84**		**64.32**		**106.50**		**134.11**		**159.73**		**69.76**		**114.59**		**157.16**		**86.06**	

Note:

- Norm. = Normalised score; Weig. = Weighted score

Calculation:

- Weighted score regarding one assessment criterion: (3)=(1)×(2)

Where,

- is generated in focus group meeting, can be found in Table 7.25 (in Chapter 7)
- can be found in Tables A4-1 and A4-3

- Total weighted score of one sustainability pillar: (4)=$\sum(3)$ of one retrofitting activity

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