Environmental and economic multi-criteria evaluation framework of residential buildings retrofit scenarios. A case study in Ningbo

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Abstract

Rapid economic development and high urbanization rates that have been present in China during the past several decades led to a drastic increase in energy consumption throughout all industries and sectors. One of the main contributors to the country's total energy demand is the building sector, and residential buildings are responsible for nearly half of that contribution. Driven by higher living standards, growing income, and increasing urbanization, the total energy consumption of public and residential buildings is expected to continue rising. The worldwide concern for global warming, climate change, and environmental pollution problems calls for a decrease in energy demand in each country, including China. Improving the energy performance of existing residential building stock through retrofits is imperative to partially lift the pressure exerted on China's energy sector and environment. And while in the northern part of the country pilot building retrofit projects started to occur, the southern part of China, especially Hot Summer and Cold Winter (HSCW) climate zone including Ningbo municipality, is yet to follow on this innovation.

Energy consumption decreases brought by building retrofits directly depend on the extent of the retrofits with major interventions often leading to greater energy savings and consequently building running costs reductions. On the other hand, however, complex retrofits require large initial financial investments that must be accounted for when selecting a building retrofit scheme. Considering the environmental side of building

retrofits, energy demand reductions decrease the greenhouse gasses (GHG) releases, but the manufacturing, delivery, and installation of new equipment and materials generate emissions. Thus, a perfect balance must be achieved between many economic and environmental criteria to make sure that the proposed retrofits are affordable and financially and environmentally beneficial.

Accurate estimation of building energy demand and the potential effect of retrofit installation depends on various factors that include both building parameters and occupancy behaviours. The residential building sector presents numerous buildings with different construction materials, heights, forms, and shapes. All of these parameters and many others are important to consider during retrofit assessments. In addition to that, the users' interaction with heating and cooling equipment are detrimental influencers on the energy demand in buildings, therefore, they must be accounted for in retrofit scenarios evaluation research.

This thesis explores methods to improve the energy performance of Ningbo city's residential building stock while simultaneously addressing the aforementioned problems. Based on the analysis of the residential building stock of Ningbo municipality, 21 building typologies were created. Representative buildings from 15 of the oldest ones among them were modelled as the baseline for retrofit scenarios assessment. The local occupancy profiles including heating and cooling equipment and regime preferences were designed based on the data collected via questionnaire to ensure the energy simulation results are as

close to the real ones as possible. Individual and combinatorial installation of different variations of retrofits for 12 active and passive building systems were evaluated following the developed EE Score assessment framework. The most financially and environmentally beneficial retrofit scenario was established for each analysed building topology. The developed EE Score assessment framework and its results on Ningbo city’s residential building stock can assist building stakeholders, residents, facility managing companies and governments in the decision-making process regarding suitable building retrofit scenarios selection. The other outcomes and discoveries made in this thesis can be used to expand further research aiming at improving energy performance, indoor environment quality, and occupants’ satisfaction with the buildings.

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Nomenclature

AC	Air Conditioning
ADENE	Portuguese Energy Agency
AEC	Architecture, Engineering, and Construction
AIC	Akaike’s Information clustering Criterion
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCA	Building and Construction Authority
BDS	Building Description System
BIC	Bayes Information clustering Criterion
BIM	Building Information Modelling
BREEAM	Building Research Establishment's Environmental Assessment Method
BREEF	Building Retrofit Energy Efficiency Financing
BRI	Building Related Illness
CDD	Cooling Degree Day
CFL	Compact florescent light
CIBSE	Chartered Institution of Building Services Engineers
CNY	Chinese Yuan

CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Coefficient of Performance
DECC	Database of Energy Consumption of Commercial buildings
DER	Deep Energy Retrofit
DHW	Domestic Hot Water
DOE	Department of Energy
EE	Economic and Environment
EED	Energy Efficiency Directive
EOD	Earth Overshoot Day
EPBD	Energy Performance of Building Directive
EPC	Energy Performance Certificate
EPS	Expanded Polystyrene
ETL	Extract Transform Load
EUI	Energy Usage Intensity
FOA	Food and Agriculture Organisation
FYP	Five Year Plan
GDP	Gross Domestic Product

GHG	Greenhouse Gas
GIS	Geographic Information System
GWP	Global Warming Potential
HDD	Heating Degree Day
HR	High-Rise
HRP	High-Rise Panel
HRT	High-Rise Tower
HSCW	Hot Summer Cold Winter
HVAC	Heating, Ventilating, and Air Conditioning
IAQ	Indoor Air Quality
IECC	International Energy Conservation Code
IFC	Industry Foundation Class
IIC	Initial Investment Cost
INE	Portuguese Statistical Institute
ISBA	Interaction-Soil-Biosphere-Atmosphere
ISTAT	Italian Institution for Statistical Analysis
LCA	Life Cycle Assessment
LCC	Life Cycle Cost

LCIA	Life Cycle Inventory Analysis
LED	Light-emitting diode
LEED	Leadership in Energy and Environmental Design
Low-E	Low-Emissivity
LR	Low-Rise
MANOVA	Multivariate Analysis of Variance
MDA	Multiple Discriminant Analysis
MoHURD	Ministry of Housing and Urban-Rural Development of China
MR	Middle-Rise
Mtce	Megatons of coal equivalent
Mtoe	Megatons of oil equivalent
NEEAP	National Energy Efficiency Action Plan
NO_x	Nitrogen oxides
NPV	Net Present Value
nZEB	Nearly Zero Energy Building
PAH	Polycyclic aromatic hydrocarbons
PBE	Private Building Efficiency
PBP	Payback Period

PM	Particulate matter
PV	Photo voltaic
SBS	Sick Building Syndrome
SETAC	Society of Environmental Toxicology and Chemistry
SHW	Solar Hot Water
SO_2	Sulphur dioxide
SSE	Sum of squared errors
TABULA	Typology Approach for Building Stock Energy Assessment
TEB	Town Energy Budget
WWR	Window to Wall ratio

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1 Chapter 1. Introduction

1.1 Statement of problem

1.1.1 Sustainability and building sector

Our planet's ecological systems have been nourishing and maintaining life for millions of years, providing clean water, fresh air, food and shelter as well as protecting all life from external harmful radiation. All the resources that Earth is capable of giving are essential for human survival. However, these resources are not infinite and with the recent increase in population and rising living standards, human demands have been stretched beyond the planet's capabilities to replenish. With the understanding of the impact that the anthropogenic activities leave on the ecosystem came the premise of sustainability and sustainable development. Sustainability emphasises the importance of efficiency in all systems and calls for maintaining the world the way it is today to provide future generations with all the possibilities we currently have to meet their needs.

However, the world population is still expected to be increasing in the next several decades, and with that the world energy demand (United Nations, 2019c). From 1971 to 2019 the world total final energy consumption increased 2.35 times from 4242 Mtoe to 9984 Mtoe driven by rapidly increasing population and rising urbanisation rates (U.S. Energy Information Administration, 2021). The main three contributing sectors were industry (31%), transportation (35%) and residential buildings (20%). In China, around 20% of the total energy consumption is attributed to the energy used in commercial, public and residential buildings. In 2018 the total building energy demand in China was 1123 megatons of coal equivalent (Mtce) with the urban and rural residential sector contributing to almost a half of this amount (Guo et al., 2021). By 2050 the residential energy consumption per person in China is expected to double due to continuing urbanisation, rise in income, increased access to electricity and electrical equipment and raised living standards. This indicates the importance of decreasing the energy demand in residential buildings through enforcing the high energy performance of new and existing buildings.

All the newly built buildings should satisfy the requirements stated in relevant building codes and standards for the period they were constructed. Years after the building has been handed in, however, there is no party responsible for the post-occupancy evaluation of the building energy performance and the investors do not have to keep the building up to the new standards (Wang et al., 2015a). This makes the already-constructed building stock unaffected by the new standards. The release of design standards for the newly constructed buildings was happening in different years for different climate zones in China. In the hot summer cold winter (HSCW) climate zone the first building energy efficiency standard was released in 2001 (Ministry of Construction of PRC, 2001). Based on that and on the fact that according to MoHURD (2018) the general buildings should be designed to have a lifespan of 50-100 years, it can be said that many inefficient buildings constructed in the HSCW zone before energy efficiency standards are in use today. Moreover, all the buildings constructed from the year 2000 should be in use in 2050. Thus, to address the high energy demand in residential buildings in China, this research focuses on analysing how the residential building stock can be improved sustainably with the financial and environmental concerns in mind.

1.1.2 Importance of local characteristics

Through incorporating sustainable goals into the China's Five Year Plans and participation of some cities in the C40 building programme, China has been gaining experience in residential and commercial building retrofit as well as integrating renewable technologies into buildings. However, these pilot projects are limited in their application and as for the retrofit, they are mostly localised in the northern part of the country, where the climate is the harshest and buildings need to withstand very low winter temperatures. Nonetheless, in the HSCW zone, the temperatures in winter can drop below 0°C, and in summer the temperatures stay above 30°C for many hours continuously during the day. This highlights the importance of introducing retrofit measures that could suit the local climate reducing the heating energy requirements during winter as well as cooling energy required in summer.

In addition to the climate difference between the northern parts of China and the HSCW climate zone, there is also an occupancy pattern difference that has been observed in other research (Hu et al., 2016, Yan et al., 2019). Since the majority of residential buildings in the HSCW zone (especially the older ones) do not have central heating, the occupants have to rely on personal portable electric heaters or split air conditioners to meet their indoor thermal requirements. These types of equipment are often less efficient than central heating requiring more energy to maintain comfortable temperatures. Moreover, unlike the central heating that runs on a 24/7 basis, residents tend to use decentralised individual heating systems only when and where required.

According to the national and local building energy efficiency standards (Ministry of Construction of PRC, 2001, Ministry of Construction of PRC, 2010, Ministry of Construction of Zhejiang, 2015) when performing a building energy simulation the heating and cooling system settings are suggested to be set on continuous operation. This is not representative of the actual air conditioning schedules data collected by other research in the HSCW zone. The importance of the introduction of actual human behaviour into the energy simulations to ensure its accuracy has been discussed in many studies (Gill et al., 2010, Hoes et al., 2009, Hong and Lin, 2013, Paone and Bacher, 2018, Sun and Hong, 2017, Eguaras-Martínez et al., 2014). Occupants' interaction with building services can account for up to 30% of the difference in building energy demand between inclusion and exclusion of occupant behaviour from the simulation (Eguaras-Martínez et al., 2014, Gill et al., 2010). However, currently, there is a limited number of research on HSCW residential building stock energy demand with the inclusion of intermittent space conditioning and none on implementing these occupancy patterns in a building retrofit scenario evaluation study. This thesis attempts to fill this gap.

1.1.3 Cost-effectiveness and environmental impact

Depending on the level of interference with the building, retrofit's initial cost can be different. Major retrofits require a substantial amount of new materials, labour hours, and expensive equipment, therefore, they are usually costly. However, greater interventions usually yield greater energy reduction results and consequently reduced building running costs. An optimal balance can be achieved when carefully evaluating the initial investment cost of the retrofit and expected energy savings associated with it. Retrofit measures presenting inadequate financial performance should be rejected, while those that can repay in energy reductions for their installation and return some of that investment can be proposed for installation. Nonetheless, the initial investment cost should be maintained at the minimum value possible to attract more participants into energy-saving retrofitting with the potential to expand it if finances allow. Considering the influence of local characteristics presented by intermittent air conditioning behaviour, the financial problem of retrofitting in the HSCW zone could present a greater challenge than in other parts of China. In addition to that, some of the existing research states that the low electricity prices in China make retrofitting non-profitable and less attractive for investors than in European countries (Wang et al., 2015b, Ouyang et al., 2009). Thus, the economical part of the retrofit should be taken into high consideration.

Building energy demand reductions brought by retrofit integration not only have a financial impact on the building life-cycle but also the environmental. Decreased energy consumption means a smaller amount of electricity or gas supplied to the buildings, which consequently leads to reductions in emissions associated with burning fossil fuels. The purchase of the materials and equipment necessary for retrofit, however, results in the generation of pollutants and emissions due to the products' manufacturing, transportation, raw materials extraction, etc. Therefore, all the retrofit options suggested by this research should be assessed on their environmental impact during their life cycle to ensure the overall reduction of emissions.

To meet the requirements highlighted above and select the best economically and environmentally retrofit options, Life Cycle Cost (LCC) analysis and Life Cycle Assessment (LCA) are conducted in this research.

1.2 Research Gap

The research gap identified in existing literature can be summarised in three points:

1. The level of detail of existing studies on residential building stock in HSCW climate zone (both physical attributes and energy consumption) is not comprehensive enough to execute building retrofit scenarios research.

2. Building energy efficiency standards in China state to perform building energy simulations with 24/7 operational heating and cooling services. As a result, a

prevailing number of building retrofit research in China uses this operation mode, and none of the existing retrofit research on HSCW zone's building stock implements intermittent part-time part-space heating and cooling.

3. Lack of research on retrofit measures evaluation for residential buildings in HSCW climate zone with consideration of both environmental and economic aspect.

1.3 Aims and Objectives

This research aims to evaluate the cost-effectiveness and environmental benefits of energy retrofitting residential building stock in the HSCW climate zone accounting for local occupancy patterns and present the best retrofitting scenario. The objectives of the research can be divided into four main parts: that which establishes the research scope and direction, second one analyses the local residential building stock, next develops and verifies building models used in retrofit measures simulations, and the last providing the economic and environmental overview of the retrofits.

1.3.1 Objective 1

The first objective presents an exploratory phase of the research. It allows for familiarisation with the subject, establishes research direction and scope using a literature review. At this stage, the drivers for residential building energy retrofit are reviewed, as well as its benefits, limitations, most common applications and data required to efficiently perform it. This objective also covers the methods and techniques to collect and analyse these data. It is necessary to study the existing procedures to select the ones that are to be used in this research. This objective can be further split into sub-tasks:

- Review the drivers for residential building energy retrofit and identify why it is important to perform residential building energy retrofits in China;
- Identify the data required for an efficient decision-making process on a building retrofit;
- Review the current state of residential building retrofit practices and their common application both internationally and in China;
- Review the available methods to represent a city's residential building stock and evaluate its energy performance to identify the ones that will be used in this research;
- Review the techniques used to analyse residential building stock data;
- Review the techniques used in evaluating various building retrofit scenarios and assisting in the decision-making process to develop an economic and environmental assessment framework.

1.3.2 Objective 2

This objective focuses on the collection of data on the Ningbo city's residential building stock, its analysis, and the creation of representative building models that are used further in the research for energy efficiency and retrofits evaluation purposes. The sub-tasks for this objective are:

- Perform the data collection of Ningbo city's residential building stock envelope characteristics on a representative sample;
- Analyse the collected data to establish prototypical building forms present in the Ningbo city's residential building stock;
- Using findings from the previous sub-task, develop representative reference models of the prototypical building forms.

1.3.3 Objective 3

Objective 3 focuses on investigating, analysing, and delivering the representative occupancy patterns into the building energy models to adjust them to the local characteristics for further simulations. During this step, the data on building energy usage intensities, that is required in the next objective, is also collected and the developed models are validated. The sub-tasks for this objective are as follows:

- Investigate the energy consumption of Ningbo city's residential building stock and especially the energy usage intensities in different building types;

- Investigate and analyse the occupancy, heating and cooling patterns present in the residential buildings of Ningbo;
- Develop the building energy models using findings of the previous sub-task;
- Using findings from previous tasks, validate the developed reference models.

1.3.4 Objective 4

The final objective compiled the findings of the sub-tasks carried out previously and applied them to evaluate the cost-effectiveness and environmental benefits of energy retrofitting residential building stock in the HSCW climate zone and Ningbo city in particular. The proposed framework is verified and evaluated; the implications it has for residents, government, and management companies are considered and discussed. Finally, recommendations for future research on expanding and deepening this study are given. This objective compiles these sub-tasks:

- Apply the proposed economic and environmental assessment framework on Ningbo city’s residential building stock using the reference building models;
- Outline the most economic and environmental retrofit packages for Ningbo residential building stock;
- Establish the results of the proposed framework and discuss its usefulness and impact on the occupants, government, and residential compound management companies;

- Propose the recommendations for future research and improvements.

2 Chapter 2. Research Background

2.1 Introduction

Our planet’s ecosystem is a dynamic self-sustaining and self-regulating system. Its ability to provide humans and animals with clean air, water and fresh food is essential for the survival of humankind. However, the recent boom of development, irrational consumerism, rapid urbanisation and population increase stretch the demand for resources beyond Earth’s capability to provide. Thus, sustainable practices are necessary to take place to ensure humanity’s survival and prosperous living.

This chapter explores the definition of sustainability and sustainable development and discusses all the environmental aspects that are of concern when considering sustainability. The relationship between sustainable development and the building sector is also established here. Based on the overview of environmental challenges that China faces and how buildings could address that issue it is argued that building retrofit must and will be given higher attention in the future, which establishes the research aim of proposing retrofit scenarios for the HSCW climate zone of China.

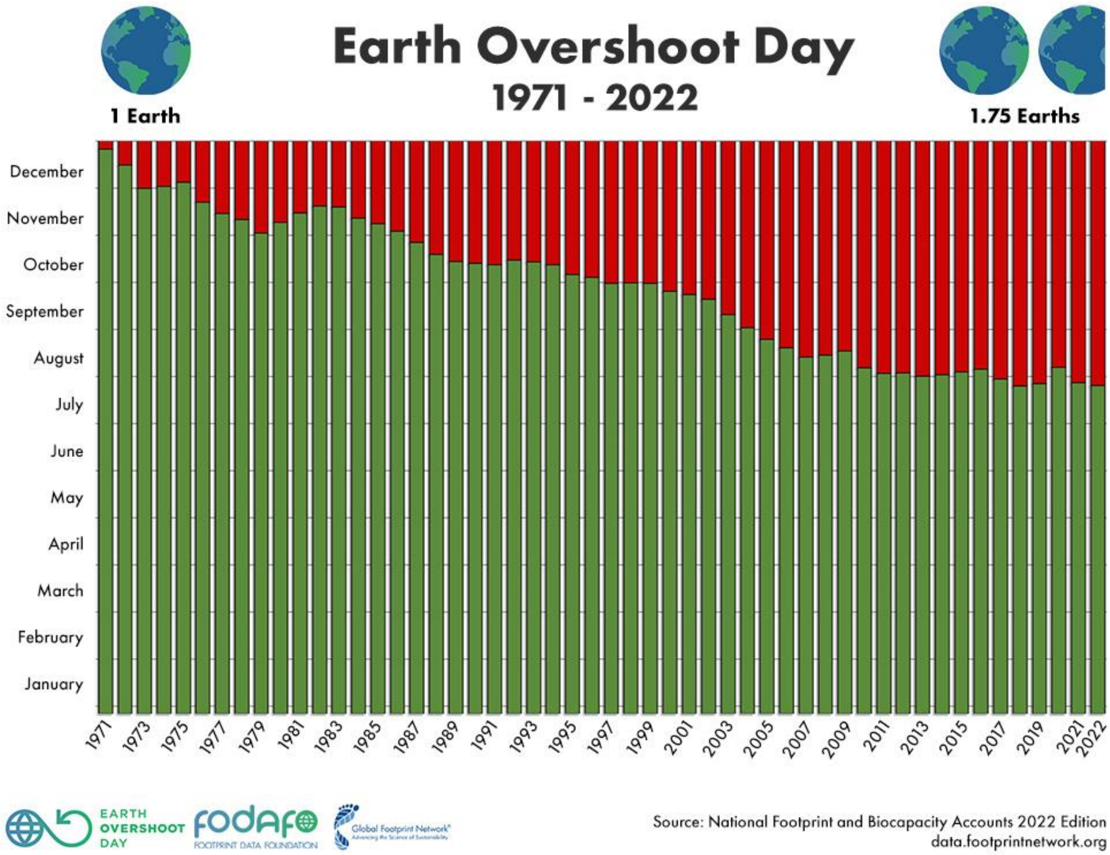
In addition to that, this chapter argues the definition of retrofit used in this thesis and discusses international policies and targets towards sustainable urban development and building retrofitting priority. Lastly, international and local examples of successful building retrofit execution are reviewed.

2.2 Sustainability and sustainable development

Since the beginning of human history, the ability to harness energy was the driving force for progress. From the understanding of how to create and use fire to cook food to the Industrial Revolution, energy has played an essential part in human development. Nowadays, all modern technologies rely on energy sources, and while our systems become more advanced and energy-efficient, it has also become clear that there is a limited amount of resources available to us.

There is only one planet that is known to be capable to support human lives, therefore, it is important to maintain it habitable. Earth's ecosystem is dynamic, it is capable to withstand many disturbances, resisting the changes and returning to the initial state. It can produce oxygen, grow plants, filter water, clean air and support animal life. Thus, if one of the types of animal population increases during the resource-rich period, it will in time stabilize when reaching the food supply or space limit. Slight variations in seasonal average temperatures or precipitation, wildfires, hurricanes and flooding are all short-term changes, from which the planet can recover. The recovery time greatly depends on the severity as well as the frequency of the disturbances. If the changes are consistent or of great magnitude, the ecosystem might reach its threshold and alter beyond its ability to return to the initial state and a different regime of processes and states is created (Chapin et al., 2011).

The idea to view our planet as a huge resource bank that replenishes its assets at a certain rate every year has led to the development of the Earth Overshoot Day (EOD) concept (previously known as Ecological Debt Day). EOD is an approximately calculated calendar date when “humanity’s demand for ecological resources and services in a given year exceeds what Earth can regenerate in that year” (Earth Overshoot Day, 2022). The regenerative capabilities of the planet are calculated based on the current state of the planet’s eco-system; i.e. the amount of oxygen regenerated in a year depends on the area of the land covered with forests that particular year. Therefore, if humanity’s requirements exceed the amount of replenished resources, not only do we consume the next year’s resources, but we might also decrease the Earth’s ability to regenerate. Figure 2.1 shows that starting from the beginning of 1970s the humanity has been consuming more than the planet is capable of renewing, shifting the overshoot day from the end of the calendar year to the late July. In 2022 it is estimated that to meet all of our requirements for that year, we would need 1.75 Earths. These increasing demands create consistent disturbances in the Earth’s ecosystem, results of which have already begun to be observed contributing to long-term consequences (Rogers et al., 2008).



Source: National Footprint and Biocapacity Accounts 2022 Edition
data.footprintnetwork.org

Figure 2.1 Earth Overshoot Day graph (National Footprint and Biocapacity Accounts, 2021)

However, not all of the resources that are being harvested or collected end up being consumed. According to the Food and Agriculture Organisation of the United Nations (FOA), roughly one-third of the worldwide produced food is being wasted (FAO, 2013). The number varies depending on the country: low-income areas waste less and high-income areas waste more. This imprudent usage of natural resources creates an unnecessary waste of clean water, releases a considerable amount of carbon into the atmosphere, and leads to deforestation and soil contamination.

Additionally, not all of the renewable resources available on our planet are being harvested. The research done by Marvel et al. (2013) shows that the global energy demand is around 5% of what could have been generated using surface-placed wind turbines and 1% of the high-altitude wind power. The United Nations' World Energy Assessment (United Nations Development Programme, 2000) estimated that the world's harvestable solar energy is almost 100 times greater than the current energy demand. Based on this, it can be said that there is a great potential to make our systems and technologies more efficient and to source our energy from renewables in a sustainable manner.

The term sustainability has gained wide use over the past two decades driven by the evidence of global environmental changes. However, the ideology of preserving the order and maintaining the equilibrium of the ecosystem can be dated back to 600 BC. Lao Tzu (also known as Laozi), an ancient Chinese philosopher, thought that people should preserve the world around them and that any changes to the natural system will affect their quality of life (Kohn and LaFargue, 1998). Today, the term sustainability represents a bridge between the environment and development. It has evolved from being mainly applied to the ecological aspect of life (i.e. maximum sustainable forestry cut, maximum sustainable yield) to capturing the economic, social equality and environmental aspects of the progress (Rogers et al., 2008).

One of the first definitions of sustainable development was given in 1987 in 'Our Common Future' report by Brundtland Commission stating that sustainable development is the development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). Other definitions imply not only maintaining the current quality of life while meeting the ecological limits but also increasing the living standards. Thus, the International Union for the Conservation of Nature (IUCN/UNEP/WWF, 1991) defined sustainability as “improving human life while living within the carrying capacity of the ecosystem”. Munasinghe (1993) additionally states the difference between ‘survivability’, which is being able to sustain welfare above a certain minimum, and ‘sustainability’, which is maintaining living standards non-decreasing (either equal or rising).

It is essential to reach a balance between the environment and progress since if sustainability is not obtained, the global environmental issues will pose a big threat to the Earth’s ecosystem and consequently to human lives. Some of these environmental issues implicated in sustainable development are climate change, population growth, the limited amount of resources, generated waste, loss of biodiversity, and air pollution. While they all have influence on the rural and urban built environment, some, like climate change, population growth, and air quality have a more direct impact.

2.2.1 Climate change

Earth’s climate is a dynamic system that naturally changes in cycles from hot tropical conditions to ice ages. Evidence of the temperature changes as well as the fluctuations in carbon dioxide (CO_2) gas level during those periods were observed by scientists while studying the ice cores from the Poles (Stoller-Conrad, 2017). Those changes in the environment happened at a slow rate through thousands of years.

Since the Industrial Revolution, the energy demand has drastically increased requiring great amounts of fossil fuels to be extracted from the ground and burned. These activities increased greenhouse gasses (GHG) levels in the atmosphere, most notably carbon dioxide, trapping the heat from the sun in our planet and warming it up. The recent global rise of temperature has been more extreme in the past 35 years with the record hottest years happening since 2014 (NASA's Jet Propulsion Laboratory, 2020). To escape the heat people rely on conditioned indoor environments, which need to be capable of addressing the raising the temperatures and meeting the comfort requirements with little reliance on air conditioning systems.

The man-made exacerbation of natural variations in global temperatures leads to an unsteady warming phase of the planet, creating areas that are heating up quicker and more rapidly than others. What took thousands of years previously is happening in decades now. The observed consequences of global warming include melting of ice glaciers, shrinking of ice sheets, sea-level rise, flooding in some areas and draughts in others and changes in weather patterns. Thus, in the northern hemisphere the summer heatwaves are becoming more severe, the hurricanes are becoming stronger and more intense and the absorption of CO_2 by the oceans increased the acidity of the ocean waters by 30% (NOAA National

Centers for Environmental Information, 2019). These changes in the environment are already translating into economic losses as well as human losses.

2.2.2 Population growth

For many centuries the world population has been below the 1 billion line until the rapid population growth started at the beginning of the 20th century (the world at six billion). The two billion mark was hit in 1927, and in 2019 the world population reached 7.7 billion people (United Nations, 1999). This dramatic change places an enormous burden on the planet's ecosystems in terms of extraction of natural resources and generation of waste and pollution.

Nowadays, even though the population is still increasing, the rate of increase on average declines. Different areas in the world have different population trajectories, with negative population growth in high-income European countries and the fastest positive growth occurring in African countries. This decline can be attributed to many factors and their combinations with the most influencing once being the average income growth, family planning and education of women (United Nations, 2019b).

Nonetheless, population growth is not the only last century's tendency influencing the world's sustainability. In 1950 New York City was the only megacity with a population above 10 million (Rogers et al., 2008), while today, there are over 30 megacities (United

Nations, 2019a). People migrate to the cities in search of a better quality of life as the main economic activities are centred in urban areas. The growth of urbanisation creates a huge ecological footprint as the rural area that is required to support a city's life (grow food, provide clean water, dispose of waste, etc.) is many times greater than the city's area (Deng and Cheshmehzangi, 2018). Additionally, large distances in big cities make it essential for people to have cars, creating road traffic congestions and releasing tons of emissions into the air.

2.2.3 Indoor and outdoor Air Quality (health)

Air pollution is the presence in the air of one or more substances at a concentration or for duration above their natural levels, with the potential to produce a negative effect on human health and/or the environment (Seinfeld and Pandis, 2006). Many ambient air pollutants, such as ozone, particulate matter (PM), sulphur dioxide (SO_2), carbon monoxide (CO) and polycyclic aromatic hydrocarbons (PAHs), are present in the air in certain concentrations naturally. However, anthropogenic activities such as fossil fuel combustion increased the amounts of these pollutants to levels threatening the health of people and the ecosystem (IARC Working Group on the Evaluation of Carcinogenic Risk to Humans, 2016). Additionally, the last century's human activities introduced other new pollutants to the planet's systems.

Ambient air pollution poses serious health risks increasing the chances of stroke, heart diseases, lung cancer, urinary tract and bladder cancer, asthma, and other respiratory diseases. The World Health Organisation (2018) estimates, that outdoor air pollution caused 4.2 million premature deaths in 2016. These deaths are primarily attributed to the increase in $PM_{2.5}$ levels, which cause cardiovascular and respiratory diseases as well as cancer.

Indoors, if the fresh air income is not being filtered, the air might contain the same pollutants as outdoors since the ambient air is the source of air income in buildings. However, the indoor air also contains other polluting gasses and particles, mainly released by fuel-burning combustion appliances, building and furnishing materials, furniture, and facility cleaning and maintenance products. Different air pollutants can cause acute and chronic diseases.

The indoor air quality (IAQ) is often associated with sick building syndrome (SBS) phenomena, which is described by US EPA (1991) as ‘situations in which building occupants experience acute health and comfort effects that appear to be linked to time spent in a building, but no specific illness or cause can be identified’. When the symptoms describe a diagnosable illness that can be attributed to a particular airborne contaminant, the building-related illness (BRI) term is used. Thus, different air pollutants can cause acute (headache, dry eyes, sore throat, dizziness, etc.) and chronic (respiratory and heart diseases, cancer) illnesses (Mendes and Teixeira, 2014, Jafari et al., 2015). With this said, the IAQ can influence both the occupants' productivity and health (Collinge et al., 2014, Fisk and Rosenfeld, 1997).

2.3 Drivers for sustainable development and retrofit in China

Since the Opening of China and its economic reforms starting in 1978, the Chinese economy has seen rapid growth with GDP (gross domestic product) increase averaging around 10% per year (U.S. Energy Information Administration, 2019). The reforms included shifting the ownership and control over the resources and production from being centrally state-owned to being private. The de-collectivization of agriculture created a household responsibility system, which drastically improved the agricultural production efficiency and nearly halved the food prices (Huang et al., 2008). These increases in agricultural efficiency allowed a big portion of workers, who were recently farmers, to work in the industry and other services without the decline in food production. Many people seized this opportunity to improve their living standards and move from the countryside to cities, which resulted in a rapid rise in urbanisation rates.

The Open Door policy allowed foreign businesses to enter China's market, boosting economic growth and creating special economic zones for international investment. Cheap labour costs and lack of environmental and safety standards in China attracted many high-income countries to move their energy- and pollution-intensive factories in a search for low production costs. At the same time, pursuing average living standards improvement and fighting poverty, the main goal above all others for China was economic growth. This led to widespread implementation of unsustainable practices, resulting in economic, social, and environmental imbalances such as air and water pollution, soil degradation and the creation of big economic gaps between urban and rural areas.

In the late 1990s and the beginning of the 2000s, China understood that its pattern of development was threatening the health of the society and the ecosystem, and started to implement the environmental changes in its Five Year Plans. Since then, some policies have been adopted to reduce the energy demand, support renewable energy resources, and reduce the taxes for energy-efficient technologies. Many standards were released such as energy-efficient design standards for buildings, appliances standards, transportation emissions standards, etc.

Nonetheless, the total energy supply in China is still rapidly growing, surpassing all other countries, including the previous leader - the United States, and reaching about 3400 megatons of oil equivalent (Mtoe) in 2019. Almost two-thirds of this energy supply was provided by coal, while biofuels, hydro, wind, solar and other renewables accounted only for around 9% (IEA, 2022). The main contributor to the total energy consumption in China is Industry taking 49.4% of the total energy demand; the second biggest portion of it, 16.7%, takes residential building energy consumption.

China holds the position of the largest coal consumer in the world, and since coal is a very carbon-intensive fuel, its burning releases massive amounts of CO_2 gas into the atmosphere, making China also the leader in this greenhouse gas emissions. Not only does the coal consumption result in global warming, but it also creates an air pollution problem for China, leading to many premature deaths due to cancer, cardiovascular and respiratory diseases (Hsu, 2013). According to China's Ambient air quality standards (Ministry of Environmental Protection, 2012), in 2019 none of the 123 key cities listed in China Statistical Yearbook (China Statistics Press, 2019) satisfied the maximum half a year average limit of $PM_{2.5}$ levels for the first grade air quality and only 25% of cities met the requirements of the second grade air quality limit. For PM_{10} levels, only one city met the first grade maximum limit and around 40% of cities satisfied the second grade air quality requirements.

The air pollution problem in China is not only the result of coal usage as a primary source of energy. China has been the world's manufacturing engine for many years, therefore, much of the emissions, including CO_2, SO_2, NO_x (nitrogen oxides), HAPs, PM, lead, mercury, and other heavy metals, can be attributed to the production of exports. Thus, if the air pollution situation in China is to be improved and if the global warming is to be kept within the 2°C bracket established by the Paris Agreement (United Nations Framework Convention on Climate Change, 2015), immense changes in the industry should be made following the direction of low-carbon and low-emission technologies.

In addition to the air pollution problem, China suffers from ground and surface water pollution. Wu and Chang (2020) state that by the end of the 20th-century water shortages have become a big problem for 400 out of 650 cities with a population of over 200.000. Rapid urbanisation and industrialisation led to water quality degradation especially in the eastern side of the country, (where the main part of major cities and industries is located along the sea coastline and the rivers) and over-exploitation of groundwater in the north. According to Wu and Chang (2020), there are four key sources of water pollution in China: saltwater intrusion due to groundwater over-exploitation, nitrate pollution due to industrial and agricultural wastewater, petroleum pollution and landfills leachate. These water pollution problems can be addressed with upgraded technologies, wastewater treatment, water-efficient equipment, installation of proper filters and overall decrease of unnecessary water usage and solid waste generation.

The energy consumption in China is expected to still be rising. While the industrial energy consumption growth has stabilised to some extent and is thought to be only slightly rising in the future, the energy demand in residential and commercial buildings is predicted to double by 2050 (U.S. Energy Information Administration, 2021). This rapid increase is driven by growing income, increasing urbanisation, increasing living standards expectancy and rising amounts of electrical appliances and equipment. From 1123 megatonnes of coal equivalent (Mtce) consumed by China's building sector in 2018, almost half of it was attributed to urban and rural residential buildings (Guo et al., 2021). Improving the energy efficiency of both newly constructed and existing residential buildings is essential for

China in order to mitigate the effects of environmental pollution and thus contribute to the mitigation of climate change.

When a new building is constructed, it has to follow the local as well as national building design standards, which usually describe compulsory indices (maximum allowed thermal transmittance of different building elements, minimum efficiency of the equipment, etc.), or performance indices (overall minimum requirements for the building envelope), or annual energy consumption indices (maximum expected energy consumption determined through computer energy simulation), or a combination of these three indices (Yu et al., 2009a). These standards are regularly updated to represent the modernised building technologies available at the time of construction and push the industry into the direction of securing the energy efficiency for the future. Much of the research worldwide is done on designing passive, zero energy, zero carbon, and other energy-efficient types of new buildings.

However, in the developed countries the building stock replenishment rate is from 1 to 2% with the primal focus today being switched to preserving and improving the old buildings (Shah, 2012). In China, according to the Unified standard for reliability design of building structures (MoHURD, 2018), the general buildings should be designed to have a lifespan of 50-100 years. Thus, all buildings constructed in this century should be present in 2050, when the building energy efficiency standards will be much more sophisticated than what buildings constructed in the first and even second decade of the 21st century can offer. It should be stated that at this point in China the average lifespan of a building is shorter than the designed one since buildings are being demolished more for economical reasoning than because of structural deterioration. Nonetheless, considering the slowing of economic growth in China (in 2000-2010 the GDP growth was around 10% per year, while now it is less than 4%), the expected decline in industrial energy consumption, increasing attention in the government policies towards sustainability, and rising amount of pilot retrofit projects on the north, it is highly likely that the building refurbishment market in China will be growing.

Overall, it is essential for China to give higher priority to building refurbishment and retrofit in order to reach economic, social, and environmental sustainability. Building refurbishment requires substantially fewer materials than the construction of a new building. This in turn means less energy used, less water and air polluted and less resources (including trees) to be consumed for the production. As a result of prioritising retrofit, the wholesale of waste from the building demolition can be avoided. Additionally, refurbishment is usually less expensive, which would make it more accessible to a wider range of people than buying a new apartment. As a result, building retrofit can ensure a longer lifespan for the building while keeping it competitive in respect to other buildings on the market. Sustainable refurbishment can improve the building envelope characteristics and heating and cooling equipment, which would result in lower running costs, improved energy efficiency, decrease of environmental footprint and would allow maintaining a comfortable indoor environment in the presence of climate change. Besides that, through the preservation of old buildings, the human heritage is being preserved, keeping cities visually pleasing and interesting while maintaining their unique landscape.

2.4 What is 'refurbishment and retrofit'?

There is no universal definition for the term 'refurbishment' and various sources define it differently. Thus, Riley (2011) states that it has a very broad definition of 'work undertaken to an existing building', implying that any type of construction can be categorized as either 'new build' or 'refurbishment'. They further proceed to give a more precise definition is 'extending the useful life of existing buildings through the adaptation of their basic forms to provide new or updated version of the original structure'. Building Research Establishment's Environmental Assessment Method BREEAM (2015) defines refurbishment as a 'wide range of works to improve the performance, function and overall condition of an existing building'. Additionally, BREEAM, American Leadership in Energy and Environmental Design LEED (U.S. Green Building Council, 2006) and Australian Greenhouse Office (2007) make a distinction between a major and minor refurbishment. According to BREEAM and LEED, major refurbishment involves envelope fabric or structure modifications, services renovation (i.e. heating, ventilation, and air conditioning (HVAC)), and internal design changes. Australian Department of the Environment and Water Resources additionally includes area limitations to the definition.

Shah (2012) states that dividing refurbishment to minor and major does not fully capture changes in the building that do not necessarily affect the thermal performance but can increase the asset value. Therefore, to include all the possible upgrades and changes from light 'refresh' to complete demolition, Shah (2012) uses five levels of refurbishment: Light Touch/Refresh, Medium Intervention, Extensive Intervention, Comprehensive Refurbishment and Demolishing. The first level represents works that are mostly focused on the visual improvement of the building such as decorating, repainting, changing carpet tiles, and upgrading minor elements. Medium Intervention includes replacement of some indoor materials (i.e. floor material, wall panels, ceiling), replacement of fittings and fixtures of lighting or sanitary ware; these changes should not require a check-up with representative building regulations. Extensive Intervention implies full replacement of building services, internal and/or external envelope material changes and possible changes of the building footprint. The main objective of this level of refurbishment is to make the building competitive with respect to the average new built and to ensure its safe, healthy and comfortable usage in the next 15-20 years. Comprehensive Refurbishment touches the whole building and brings all elements (including service and structural) up to the current standards, with the extreme option of leaving only the shell of the building and reconstructing all other parts. Finally, if the outcomes of potential refurbishment options are unsatisfying, Demolition of the whole building empties the space required for new construction.

The term ‘refurbishment’ includes many other terms used instead of or in combination with it in different literature such as ‘conversion’, ‘renovation’, ‘restoration’ and ‘retrofit’ whose usage largely depends on the scope and scale of building changes and reasoning and target of the intervention. Thus, building ‘conversion’ means a change of use or function of an existing building or fitting a new use to an existing building (Remøy Hilde and Wilkinson Sara, 2012, Riley, 2011, Sedláková et al., 2020, Wadu Mesthrige et al., 2018). Additionally, it can mean a transformation of an averagely performing building to a passive or zero energy building (Asaee et al., 2018, Asaee et al., 2019, Pacheco and Lamberts, 2013). In order to do these conversions, Extensive or even Comprehensive refurbishment would be required. Term ‘renovation’, according to Ástmarsson et al. (2013) and Feng et al. (2020), is returning the looks and performance of different old or damaged building components to their original state or better for the building to meet the current standards. The main reasoning behind the renovation is the ageing of built assets and the deterioration of materials. Term restoration is used for the same reason as renovation, being the deterioration of a building, but the building itself should present a historical value that needs to be preserved (Biagini et al., 2016, Cárdenes et al., 2014, De Leão Dornelles et al., 2020, Pérez Gálvez et al., 2013). U.S. department of the Interior (2017) defines restoration as ‘act or process of accurately depicting the form, features, and character of a property as it appeared at a particular period of time by means of the removal of features from other periods in its history and reconstruction of missing features from the restoration period’. The objective of restoration is to refurbish the building while maintaining its structural and aesthetic integrity and preserving its unique historical essence. Cárdenes et al. (2014)

additionally states, that the restoration work must be well-documented in order to be able to clearly separate new elements from the original ones.

Retrofitting is defined by the Advanced Energy Retrofit Guides (U.S. Department of Energy, 2011) and Retrofit 2050 project (Eames et al., 2014) as upgrading the building by providing it with components or features that it did not have when it was initially constructed. The main purpose of this intervention is to improve the energy efficiency of the building by installing new and additional insulation materials, upgrading lighting systems, replacing envelope elements (windows and doors) with better-insulated ones, installing highly efficient cooling and heating equipment, installing renewable technology, providing the building with the smart operation and maintenance system. Since the focus of this research is to develop scenarios of increasing energy efficiency of the buildings that are not necessarily aged or deteriorated and upgrading them beyond the basic requirements of the local and national standards, the term retrofit most closely describes the interventions that are to be suggested.

2.5 Data required for building operation and retrofit

Managing any constructed facility implies sustaining and improving the quality of life and consequently the productivity of people using this facility. It involves regular maintenance of hard and soft services, systematic check-ups and at some point renovation and finally demolishing. The decision of whether or not to perform refurbishment and what systems need to be improved should be made based on discreet analysis and consideration and must take into account a significant amount of up-to-date building characteristic data. These data are equally important for the retrofit decision making.

The whole process of retrofit decision making can be divided into four stages: a) Project preliminary survey; b) Facilities performance assessment; c) Identification of possible retrofit scenarios; d) Quantitative economic comparison of options (Juan et al., 2010, Rosenfeld and Shohet, 1999, Sesana et al., 2016, Shah, 2012). The first stage reviews the legal status of the facility and retrofit. The concern is for the historical heritage, architectural look, the site space possibly needed for the facility expansion, time frame when the building will possibly be inaccessible, etc. The second stage takes into account the building's physical and functional conditions: building energy flows, unacceptable comfort conditions and inefficiencies in any of the facilities. During the third stage, the alternatives are generated. The decision-makers should decide if the building is in relatively good conditions and only local replacement of weak spots is needed, or if the building needs serious action and either treating all the components and parts that have poor performance is needed or all the systems and components are to be improved to the excellent condition. The last stage involves the comparison of these alternatives from a techno-economic point of view to find the most cost-efficient solution. During this stage considerations should be made on: initial cost, estimated economic life-span, expected maintenance costs, total construction duration, possible disruptions and interference with normal building usage practices, logistic and other indirect consequences, environmental impacts, infrastructure requirements, etc.; in overall, LCA and LCC should be performed (Rosenfeld and Shohet, 1999, Shah, 2012). Sesana et al. (2016) state, that an additional stage can be added to the process being a validation of the retrofit via simulation or real data.

In order to make carefully evaluated decisions during these four stages of retrofit a considerable amount of up-to-date data is required (Hammond et al., 2014, Jimenez-Bescos and Prewett, 2018, Juan et al., 2010, Ostermeyer et al., 2013, Sesana et al., 2016, Shah, 2012, Wang and Cho, 2015). Building, being a dynamic system, relies heavily on many variables that need to be sensibly considered and assessed for successful sustainable principles implementation into the retrofit scenario. Hammond et al. (2014) state that all of these characteristics can be divided into Building Form group and Building Function group.

2.5.1 Building Form

2.5.1.1 Location

The location of the building predetermines micro and macro climate: outside temperature, humidity, wind patterns, illuminance levels, etc. Analysis of these data allows to sensibly evaluate the year-round heating and cooling demand of the building as well as its peak load, which is essential for accurate heating and air conditioning unit sizing. It would also assist with passive energy strategies decision making during retrofit: which approaches are applicable for this specific location, how much of the energy demand can they cover and would it be possible to maintain a comfortable indoor environment implementing only passive strategies. Based on the local illuminance levels an evaluated decision regarding the installation and sizing of solar photo voltaic (PV) panels and solar hot water (SHW) can be made. On-site investigation of prevailing seasonal wind patterns would assist with the natural ventilation strategy as well as the need to block cold northern winds. For buildings in a hot climate, it is essential to capture cool breezes to decrease the building's dependency on an electric cooling system. The analysis of local humidity levels can define whether evaporative cooling techniques can be considered and if additional condensation protection of the building is necessary. Surrounding objects (such as other buildings located nearby, parks, water bodies, etc.) have the potential to influence the building's energy demand and can be benefited from: tall buildings block the sunlight, rivers and lakes act as heat sinks and trees in the parks diffuse strong winds. Furthermore, some locations would require better air filtrating technologies due to high outdoor air pollution as well as additional sound insulation in areas with high outside traffic noise to maintain a comfortable indoor environment.

2.5.1.2 *Massing and room layout*

Building orientation, on-site positioning, shape, massing and overall size greatly impact building's energy demand and the use of passive design strategies. In order to conserve the heat and reduce the amount of heat exchanged between the building and the outside environment, the building must be designed with a compact form (sphere and cube have a small surface area to volume ratio). In warm and hot climates building massing should allow for heat dissipation, therefore, complex and shallow floor plans can be considered promoting cross-ventilation of rooms for cooling. While it is often not possible to change the shape of the building during the retrofit, the probable flaws of the initial design need to be established in order for them to be accounted for in a new design. The analysis of building on-site orientation would allow blocking excessive sunlight with shading in summer preventing overheating while still allowing the solar radiation to come in during winter for passive heating if needed. Disregarding the climate, orienting the building with its longest façade towards the sun or locating larger windows on that façade maximizes natural light penetration into the building decreasing its dependency on artificial lighting systems. Careful evaluation of windows sizes and location would allow achieving the desired balance between conduction heat losses, radiation heat gains, natural ventilation through windows and natural light penetration. Room layout can be designed to encourage energy savings as different rooms are being used at various times of the day and for different purposes. The internal design should locate rooms with higher passive internal heat gains from people, equipment and lighting to colder parts of the building (north façade in the northern hemisphere) to prevent overheating. Additionally, proper consideration of which room is being used at what time of the day can assist in designing a room layout that provides morning and evening natural light penetration to the locations where it is required at that time of the day. Moreover, building layout (especially in commercial buildings) should be flexible and be adaptable for changes in internal design to cope with the users' requirements.

2.5.1.3 Roof type

The main purpose of any roof is to protect the building and its inhabitants from the outside elements. However, some roof types are more suitable for certain climate conditions, making a building more resilient and energy-efficient. If Comprehensive refurbishment is to take place, changing the roof shape might be considered. Thus, pitched roof types such as Gable, Hip and Dutch are best for areas with heavy snow and rain as their pitch allows the liquid and solid water to easily slide off; extra space created by these types of roofs is good for ventilation purposes. If the design requires additional incoming natural light, Dutch, Butterfly roof and Dormers will create more vertical surfaces that could be used for window installation or would allow larger windows; in order to bring light deep inside the building, Clerestory roof can be considered. When the amount of incoming direct light has to be minimized, Bonnet roof type provides overhanging eaves that create shading and protect walls from water damage. Flat roof can be a valuable option in sunny areas with little rainfall as it is conducive for PV panels and SHW installation or can create space on the roof for a garden and green roof.

2.5.1.4 Historical value

Historic buildings bring benefits to both local residents by beautiful view and cultural enrichment and the economy via attracting tourists from other cities and countries. It is essential to conserve them to preserve our cultural resources and heritage. As the building gets older and deteriorates with time, retrofitting is required to keep the building in use and maintain its structure and systems safe for visitors. Since for historic buildings the least possible amount of changes is preferable, there is a need to find a balance between the conservation of initial design and the requirements of new building facilities. Before retrofit consideration, it is important to collect data on what parts of the buildings must remain as they were and what could be changed without altering the historical essence.

2.5.1.5 Building envelope

Insulating properties, the thermal inertia of the materials and the amount of glazing are the characteristics determining the building's envelope efficiency. Building envelope is the barrier between the indoor environment and the outside world, it includes roof, walls, foundation (or floor), windows and doors. If designed and constructed well, building envelope can reduce and/ or slow down the heat transfer between the inside and outside and maintain comfortable indoor conditions. In order to do that, careful consideration regarding the construction and insulation materials should be taken during design and retrofit. There are three types of insulation based on its effect: capacitive, reflective and resistive. Capacitive insulation is also referred to as 'thermal mass', and while in steady-state heat flow it has little effect, its main purpose is to affect the timing of the heat flow in the presence of temperature fluctuations. The phenomenon of the time lag between the moment when a material is exposed to a different temperature and the moment when this material reaches this temperature is called thermal inertia and it is dependent on the material's specific heat, conductivity, dimensions and other factors. Reflective insulation reduces radiative heat transfer. Unlike the other two types of insulation, its effectiveness does not depend on the thickness of the material, but on the colour and reflectance of its surface. The best materials for resistive insulation (second best to the vacuum) are gasses, therefore, good resistive materials are those that trap small pockets of gas (mostly air) such as mineral wool, glass fibre, extruded polystyrene, etc. If these pockets of gas are small enough to suppress convection within them, the material will have very low overall thermal conductance. Highly efficient windows implement the same principle of trapping the gas (like argon) between the glazings, greatly decreasing the heat exchange through them. The special low-emissivity (Low-E) coating that is invisible for the human eyes reflects the solar heat in summer while allowing the visible light to go through, while in winter the same coating will keep the radiative heat inside the building. In a well-insulated building, windows account for a great portion of heat loss, therefore, high insulation of walls requires high thermally performing windows.

2.5.1.6 Air tightness and thermal bridges

Both thermal bridges and draughts created by air leakage can substantially influence the energy performance of a building increasing its reliance on mechanical heating and cooling, it can also increase indoor relative air velocity and decrease mean radiant temperature resulting in uncomfortable and unhealthy conditions for the building users. With time, as the standards for building elements' insulation qualities improve the significance of energy loss through small local areas of reduced insulation or thermal bridging increases. Bridging can not only be the result of a poor design or implementation, but also deterioration of construction materials and the building itself. Air leakage or infiltration is the uncontrolled and unwanted air movement through the gaps and cracks of building fabric. As the warm damp air passes through the envelope to the cooler places interstitial condensation can occur. Infiltration and thermal bridges both result in the creation of local cold areas which cause condensation, further damage of the materials and mould growth and, therefore, need to be accounted for during retrofit.

2.5.2 Building Function

2.5.2.1 Energy performance

The main purpose of any building is to provide a comfortable and healthy environment while consuming the minimum amount of energy. These two goals are often opposite to each other and therefore a careful balance is needed between reaching the required indoor thermal standards (temperature and humidity) and implementing sustainable technologies. Applying passive and green energy strategies allows decreasing the facility running cost and reducing environmental influence. Artificial heating and cooling equipment help to maintain comfortable indoor conditions in places where passive strategies are not sufficient. In that case, the overall energy consumed by a building would depend on the type of heating and cooling systems, their performance, efficiency and sizing. Data regarding the currently used equipment and its condition can assist in retrofit decision making. In cases where a centralized hot water supply is not provided, on-site highly efficient and well-insulated hot water systems need to be considered.

Water management – To evaluate building water efficiency and do a proper size estimation of installed or a new water supply system, past annual-use records or expected occupancy can be used. Prior to the retrofit, a careful analysis of the existing water supply system and all of its components is necessary to evaluate and locate potential leakages as well as to estimate the possibility of different water-saving techniques implementation. Installation of meters and monitoring technologies can assist with this analysis as well as help occupants to have a better understanding regarding water consumption in the building, control their water usage and encourage water saving. In order to decrease the water demand without occupants' behaviour change, water-efficient urinals, sinks, lavatories and showerheads can be fitted. If the shape of the building, its roof and gutters as well as the available space allow, a rainwater harvesting system and grey water treatment system can be considered.

2.5.2.2 Lighting

There are different simple but efficient design strategies, fixtures and materials that can enhance energy saving possibilities of both artificial and natural light. Daylight is a free and renewable source of energy, therefore, the architectural design of a building should prioritize the use of natural light over artificial. Additionally, using natural light the heat gains coming from the light bulbs and artificial lighting system components can be reduced consequently reducing the cooling loads of the building. During dark hours of the day, electric lighting is essential to maintain the normal operation of the facility, therefore, the installation of energy-efficient light bulbs, such as compact fluorescent lights (CFL) or

Light Emitting Diodes (LED) should be considered during the retrofit. Any type of light source can benefit from light coloured walls, ceiling, floor and other objects as well as from reflective materials by diffusing the light and spreading it evenly throughout the space creating ambient lighting. Additionally, any design should consider the problem of glare in rooms, where excessive direct light can cause difficulties in using computer screens or TVs.

2.5.2.3 Air quality

Sometimes the decision of retrofit can be driven by the building occupants' complaints about the indoor air quality. In this case, testing should be performed on the presence of different types of pollutants, their sources, health risks that they pose and the action required to mitigate them. Poor indoor air quality can be a sign of inefficient ventilation system, low fresh air supply rates, pollutant releasing substances and equipment or inadequate incoming air filtering technology. Before a ventilation filtering system retrofit, it is essential to know the outside air quality data to effectively choose the proper filters. After the retrofit, driven by poor air quality or not, indoor pollutants must be measured again to make sure that the new design complies with recognised standards for indoor air quality and that the newly installed equipment and fittings are not releasing dangerous amounts of pollutants. Air pollutants should be constantly monitored to maintain a healthy environment as US EPA (1991) states that air contamination is the main cause of SBS and BRI which can significantly decrease the productivity of occupants, worsen their mood and overall well-being. Long-term exposure to some of the air contaminants can cause the development of chronic illnesses such as asthma, allergy, eczema, etc. Therefore it is important to evaluate the existing ventilation system and analyse if its capabilities meet the requirements of the building.

2.5.2.4 Building and room usage type

What a building and different rooms in it are used for and what activities are being performed there predetermines the occupants' behaviour, requirements and schedule. Different rooms in a building are being used for different activities, knowing the usage type would help to evaluate how much heat will be produced and released by people and what clothing they are expected to be wearing. Both of these variables greatly affect the indoor environment conditions such as air temperature, surface temperature, relative humidity and air movement, which are essential to maintain at recommended standards levels for that specific room type to keep comfortable thermal conditions. Depending on the room type further assumptions on installed electrical appliances can be made to analyse how much passive heat will be generated by these appliances.

2.5.3 Summary of building characteristics

An immense amount of data on building characteristics is required for a successful building retrofit. As it was discussed before, they can be roughly divided into two groups: Building Form and Building Function. Figure 2.2 provides a summary of these characteristics. Building Form group contains characteristics most closely related to the architectural side of the building such as its envelope, shape, layout and value. During the various retrofit options consideration these characteristics must be accounted for, but can rarely be changed. Building function group is more closely associated with the engineering side of the building such as building services; they more directly affect users. When considering retrofit options, these characteristics are often improved upon. The colour gradient of characteristics boxes in Figure 2.2 represents the opportunity to change a certain building characteristic (e.g. location is impossible to change, while lighting can be relatively easily improved).

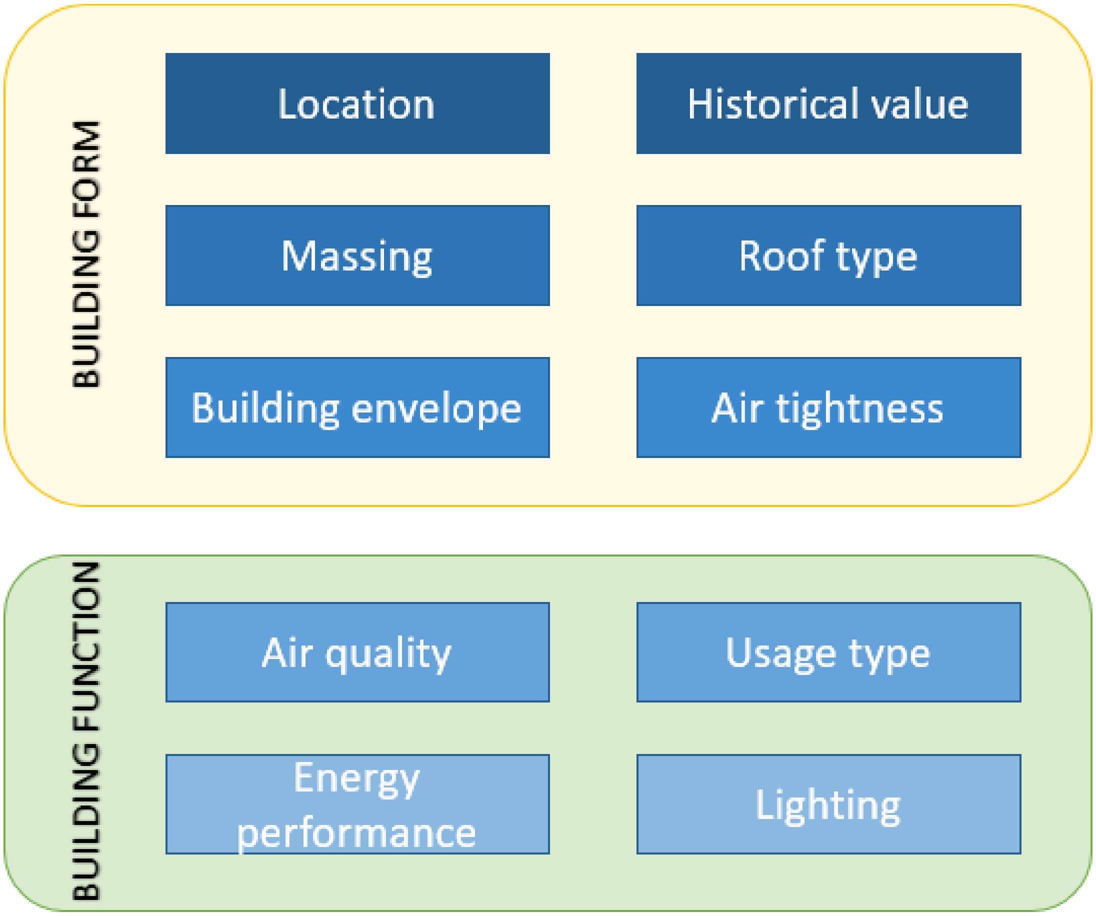


Figure 2.2 Summary of building characteristics

2.6 International examples of building retrofit

2.6.1 Overview of policies, targets, and benchmarks

In the face of climate change and environmental pollution, many countries are targeting energy-saving measures. Building design codes and standards are being toughened to promote the high energy performance of this sector. A number of refurbishment programmes, frameworks, and financial incentives are being developed to stimulate the market switching in that direction and empower small businesses and residents with opportunities to perform retrofits in their buildings.

Global Buildings Performance Network (2015) performed an analysis of the best building energy renovation policies and frameworks worldwide to establish the supporting criteria and sub-questions that would assist in developing better policy packages. The key criteria that were described as being important for a well-performing policy package included those, assessing the national targets for the energy efficiency, establishing clear standards and regulations, retrofit enabling financial incentives and funding, awareness-raising and information campaign, and overall available data on the assessment of building performance before and after the retrofit.

2.6.1.1 The European Union

In order to promote energy performance, the European Union (EU) has established two legislative frameworks Energy Efficiency Directive (EED) and Energy Performance of

Buildings Directive (EPBD) that outline a set of objectives, achieving which would ensure that the energy is used more efficiently at all stages of the energy chain from generation to end-use (Atanasiu and Kouloumpi, 2013). While EED touches all the industries and sectors, EPBD is focused more on the building sector, aiming to achieve a zero-emission and fully decarbonised building stock by 2050. Its previous target required every participating country to submit once in three years the national energy efficiency action plans (NEEAPs) to achieve the 20% energy efficiency target by 2020. Allowing countries to develop their own NEEAPs ensured the flexibility of the directive to account for differences in climatic and building stock conditions across Europe. Later, the directive was amended to reflect higher ambitions and emphasise the importance of climate action. Currently, it requires to perform retrofits of buildings owned or occupied by the central government at a rate of 3% of the total floor area per year. Besides that, a long-term strategy that would be implemented to renovate residential and commercial building stock must be developed and updated every 3 years. The next short-term goal is to reach the target of -60% of building emissions reductions by 2030 in comparison to 2015.

2.6.1.2 Sweden

Sweden has set an ambitious goal to achieve zero-net GHG emissions nationally by 2050. Being a country with a cold climate, their buildings are already relatively energy-efficient, nonetheless, it is proposed to further improve energy efficiency in buildings by 20% in 2020 and by 50% in 2050 with relation to 1995 consumption rates. To achieve these targets, high importance is placed on renovation activities with low rates of new construction.

Retrofitted buildings should comply with the same regulations as the new construction buildings, which makes it simple for the market to understand and implement. There are different centres for the renovation of different target building types: multi-family, commercial, and single-family. While they all work on different projects, they share their experiences and success as well as other companies interested in refurbishment. To raise higher investments and decrease the cost of transactions, groups of buildings are being retrofitted together, encouraging building owners to work together. Another factor that has played an essential role in national energy consumption decrease is the residents' participation. Since all the information on the building stock and the best practices are available online for anyone interested, the residents are provided with recommendations on how to reduce their energy consumption. This, as well as the national education system, creates the awareness of energy efficiency in the whole community (Atanasiu and Kouloumpi, 2013, Global Buildings Performance Network, 2015).

2.6.1.3 Germany

In Germany, the government has been establishing energy efficiency standards since the 1980s. Today their goal is to achieve 20% reductions in heating demand by 2020 and an 80% reduction in total primary energy demand in buildings by 2050. To do that, the government-owned bank KfW created a CO_2 rehabilitation programme, promoting financial incentives with higher anticipated energy performance allowing to receive greater incentives. Between the years 2006 and 2014 this programme co-financed 33% of retrofitted buildings, reduced 7.1 million tonnes per year of GHG emissions and generated up to 300,000 working places. As a result of that, Germany has reduced its dependence on energy imports and developed a framework for achieving nearly zero energy buildings (nZEB) in the future (Atanasiu and Kouloumpi, 2013, Global Buildings Performance Network, 2015).

2.6.1.4 Denmark

Denmark has been working on energy consumption reductions through establishing energy performance standards and frameworks since the oil crisis in the 1970s. Nowadays, it is thriving for 50% of its total energy demand being satisfied by renewables by 2030. With this strong commitment to sustainability, Denmark already has implemented energy regulations and taxes and has raised public information and awareness. Building renovation plays a great part in achieving their targets. With already high energy performance in the buildings, Denmark has considerable expertise in retrofitting, and there are many companies producing materials and systems for energy-efficient buildings. Therefore, establishing new standards and goals is not viewed as overcoming milestones, but as new sales opportunities that will stimulate the market. The new target set for 2050 is to reduce energy consumption in existing buildings by 35% through deep renovations and integration of all energy-saving elements. Similar to Sweden, different strategies are being developed for various building categories as they face different problems and have different retrofit potential. One of the approaches that are used to make refurbishment cost-effective is switching to the best practices and highly energy-efficient options when the object or material is to be replaced for non-energy related reasons. These reasons may include:

building component wearing out, the building being altered for new use type, or higher indoor environment quality being pursued (Atanasiu and Kouloumpi, 2013, Global Buildings Performance Network, 2015, Danish Government, 2014).

2.6.1.5 United States

With the average multifamily buildings age being around 40 years, there are a lot of opportunities to improve the residential building stock in the United States. Therefore, both the International Energy Conservation Code (IECC) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards outline mandatory measures that are to be enforced when a building undergoes a renovation. For example, if a building or a space is altered from being non-conditioned to being heated or cooled, it must comply with all the current regulations for residential or commercial buildings; if a whole building element (window, door, HVAC, etc.) is being replaced, the new equipment must also comply with the modern standards. This allows for energy-efficient technologies to be implemented during regular building maintenance practices.

The United States Department of Energy (DOE) has developed an agenda that would allow decreasing the energy consumption in buildings by 40% by 2030 through Deep Energy Retrofits (DERs) (Less and Walker, 2015). The most successful projects done with this program were said to be high energy-using buildings that required repairs and maintenance. It was also thought to be essential to involve everyone, including the occupants, in the decision-making process to choose the strategies that would be most useful for the specific project and residents. Involving occupants in the project additionally provides them with the necessary information and knowledge required to maintain the building and run it in an energy-efficient manner.

In addition to the national programmes, the states' local authorities also implement some frameworks and incentives directed to encourage energy-efficient building retrofits. The New York State was the first in the US to produce sustainability plans for the whole state. They combined the bottom-up with the top-down approaches to ensure that the residents are engaged in the reduction of their energy consumption and financially supported to perform the retrofit. All the information on measured data from previous projects before and after retrofits as well as the renovation technologies used are available for the consulting firms, service providing companies, and financers. California set a goal to get 2020 GHG emissions being equal to 1990 levels. To do that, the California Energy Efficiency Standards for Non-residential Buildings stated that all new and renovated public buildings must be awarded at least a silver LEED (Leadership in Energy and Environmental Design) rating. The building codes also require the replacement of old fixtures and elements with more efficient ones during the building renovation.

2.6.1.6 Singapore

Singapore's building sector accounts for around a half of the country's total energy consumption, which can be explained by unique 100% urbanisation rate. Thus, to decrease the country’s total energy demand the government developed a plan to “green” the new and existing buildings.

In 2005 Building and Construction Authority (BCA) launched a Green Mark Scheme – building certification framework assessing the environmental performance of new and existing buildings (Singapore Government Agency, 2022). Its aim has been to promote sustainable design, construction and operation of buildings, similar to BREEAM and LEED schemes in UK and USA, but adjusted to tropical climate with greater importance placed on the cooling and air conditioning and higher emphasis on energy efficiency and monitoring equipment’s energy performance. The points are given for energy-efficient and sustainable features and the building can be granted the BCA Green Mark Platinum, the GoldPlus, the Gold, or the Certified score based on the final results of the assessment.

Starting from 2008 achieving the minimum Certified rating of Green Mark Scheme became mandatory improving the energy performance of new buildings. The Green Building Masterplan introduced in 2013-2014 addressed the issue of energy efficiency in existing buildings through three requirements directed towards the building owners: if the cooling system is installed or retrofitted the minimum Green Mark rating must be achieved; energy audit is performed every three years; annual report on building information and energy consumption is submitted. Current aim of this program is to have 80% of buildings being green. In order to provide financial support for the green retrofit the Green Mark Incentive Scheme co-funded up to 35% of the retrofit cost, while the Building Retrofit Energy

Efficiency Financing (BREEF) provided loans to help with the upfront costs. As the result of these green frameworks and incentives, the number of Green Mark certified buildings increased dramatically over the years and the total building energy demand decreased by 21% between years 2008 and 2020 reaching average of 214 kWh/m^2*year (BCA, 2021).

2.6.1.7 Australia

In order to address the issue of climate change and raising energy consumption in building sector Australia developed two separate rating schemes for residential buildings and public buildings called Nationwide House Energy Rating Scheme (NatHERS) and National Australian Built Environment Rating System (NABERS) respectively. NatHERS has been first introduced in 1993 on a voluntary basis and has been used to estimate the energy efficiency of a home certifying it with a star rating out of 10. In 2005 new governmental regulations have required achieving 5 star rating by all new residential builds, in 2011 the requirement has been raised to 6 star rating and in 2022 it is 7 star (Seo and Foliente, 2021).

NABERS was initially developed as a voluntary building certification scheme in New South Wales in 1998 and had a 1-5-star scale representing the energy performance of a building with 5 star rating being the industry best practice. The New South Wales government later mandated the scheme with minimum requirement of 3.5 stars for all of their offices. In 2009 the scheme became nationwide and in 2011 the sixth star was added into the certification scheme driven by new technologies and overall improvement in the performance of the building stock. Nowadays, this scheme sets a requirement for reaching a benchmark of 4.5 stars for all new government buildings, major refurbishments, new leases of 2000 m^2 and more and all offices > 1000 m^2 (Mallaburn et al., 2021).

2.6.1.8 C40 Cities

C40 Cities Climate Leadership Group was started in 2005 with 18 megacities that created an agreement to cooperate on mitigating climate change and reducing pollution. Through the years the number of participating cities has increased to 96 cities that are accountable for 1/12 of the world population and accumulate 25% of the world economy. The sustainable action plans developed, shared and driven by this programme are very diverse and touch many aspects of the urban environment, such as energy and buildings, transportation and urban planning, food, waste, water, and air quality.

The Urban Efficiency II report (Trencher et al., 2017) covers the overview, characteristics and outcomes of the innovative city initiatives focused on building energy efficiency and retrofitting existing buildings in seven cities that are included in C40 Private Building Efficiency (PBE) network. The proposed methods in these cities can have mandatory or voluntary characteristics as well as a combination of the two. Thus, in Tokyo and Seoul, several thousand private sector buildings were participating and implementing the energy efficiency changes voluntarily. In addition to that, Tokyo and Shenzhen also implemented some mandatory city programmes.

Following the thought that “what gets measured gets improved”, five cities used periodical data reporting to observe the buildings’ energy consumption and GHG emissions. This allowed to observe and evaluate the progress of buildings in their energy-efficiency journey and share the successful projects with other interested parties. Six out of seven reviewed in the report cities also built the financial supportive measures, since the uncertainty and an often long payback period of retrofits make banks and lending institutions reluctant to finance these activities. Through the educational programmes, the knowledge gaps about energy efficiency, available technology, and financial support were addressed within the market and the average public. The energy reduction challenges provided the required motivation and competitiveness to intensify the efforts for improved energy performance.

The outcomes observed as a result of these programmes included all three pillars of sustainability: environmental, social, and market benefits. Thus, as a result of energy-efficiency targeting and onsite renewable energy integration, the energy and water demands and GHG emissions were decreased which in turn reduced the energy expenditures. The stimulation of retrofitting and implementation of sustainable technologies created greater awareness of the climate issues, stimulated behavioural changes, increased the number of green jobs and raised the demand for green buildings. In addition to that, deep refurbishment of buildings allowed to increase the amount of vegetation, roof gardens, green walls and green roofs, which, in combination with old buildings renovation greatly improved the aesthetics of the cities.

2.6.1.9 *Summary of international benchmarks and targets by climate*

Different climates of various countries create different building energy consumption patterns and as a result demand diverse actions to improve building energy performance. Thus, countries address this issue based on their combination of several parameters such as economy, climatic conditions and the conditions of existing buildings and built environment as a whole. In many countries the vast territorial areas present several climatic conditions requiring building energy benchmarks to include those differences in energy patterns. Thus, some countries solve this problem by comparing the current building energy demand with the one present in the same climatic area decades ago to display the improvement or to establish the future target. Others, develop their own certification schemes that take local environment and buildings' conditions into account.

Sweden – *cool continental / subarctic* – 20% of improvement in building energy performance by 2020 and 50% by 2050 in comparison to 1995 energy consumption rates; all the retrofitted buildings must comply with the current relevant building energy efficiency regulations.

Germany – *humid temperate* – 20% reductions in heating energy demand by 2020 and 80% of total primary building energy by 2050 in relation to 1980s; the government co-financed a third of building retrofitting projects.

Australia – *arid desert / steppe / dry* – benchmarking based on two national certification schemes: for residential buildings and public buildings; all new residential buildings must reach 7 star rating; all new government buildings, major refurbishments, new leases of 2000 m^2 and more and all offices > 1000 m^2 must be certified with 4.5 star rating.

Singapore – *humid tropical* – all new buildings or existing buildings with their cooling system undergoing a retrofit must be certified as green with minimum rating based of national green building certification scheme; the target is to have 80% of existing buildings being green by 2030.

2.6.2 Case studies

2.6.2.1 Terraced house

A Victorian terraced house in 89 Culford Road, London, required an extensive refurbishment (Parker, 2010). During this retrofit, the goal was to bring down the carbon emissions by 80 per cent. The main challenge with this project was to maintain its historical view, therefore, the outside of the front façade has been left untouched, while the internal frame was rebuilt to provide insulation and eliminate thermal bridges. In addition to that, the micro (or slim) argon-filled Low-E coated double glazed windows, that kept the original look of sash windows, were installed. The back of the house has been extended to substitute for the space that has been taken away by the insulation. As a result of this retrofit, high insulation and airtightness was achieved. To compensate for the lack of incoming fresh air and stacking effect, mechanical ventilation with a heat recovery unit (91% efficiency) was installed. The installation of PV panels on the roof provided around 30-40% of the electricity demand of the house.

2.6.2.2 Apartment block

A Finnish 1980s apartment building in Tampere city was renovated in line with the EU-GUGLE project (EU-GUGLE, 2020). This 7-floor building is connected to the central heating system and has a mechanical exhaust ventilation system. The façade was thought to be in a good condition with the external wall U-value being equal to 0.35 W/m^{2}K and roof U-value being 0.4 W/m^{2}K. During the renovation the 2.1 W/m^{2}K windows and doors were replaced with higher insulated ones, the light bulbs were changed to LED and a presence control of lighting was installed. In addition to that, the new layout of the heat distribution system with an exhaust air heat pump was implemented and solar collectors were installed on the roof. The measured energy consumption after the renovation shows a 36 MWh increase in electricity demand, but a 405MWh (-75%) decrease in heating energy demand. As a result, these interventions allowed to save 24000 € annually.

2.6.2.3 High-rise building

As a practical example of retrofitting a high-rise residential building, the 15-storey Thompson Garden constructed in the 1960s in Smethwick, UK, can be used (Burton, 2012). The building structure was considered to be in a fair to good condition, while the look, safety and energy efficiency required improvement. The residents were given several options of the possible results and outside looks of the building that they could choose from. As for the sustainability improvements, the wall was insulated with 80mm of mineral fibre giving the result of U-value being equal to 0.35 W/m^2K; the windows were replaced with double-glazed argon-filled timber frame windows, and a new aluminium foil roof was installed. In this retrofit, a high priority was given to recyclable and/or sustainably sourced materials. The post-retrofit energy consumption analysis showed a 40% reduction in heating and light demand, which accounted for 815 £ of annual savings.

2.6.2.4 Single apartment

In case the whole building retrofit is not possible, a single flat renovation is applicable (Burton, 2012). An apartment on the top corner of a seven-floor building was retrofitted in London, Kings Cross. The building was constructed in the 1900s with solid brick walls and no roof insulation. The retrofit was planned to solve four major problems: to save energy, improve indoor comfort, maximize the available space and improve the looks. Due to the fact, that the renovation was only for one apartment, the external insulation of the roof was impossible to implement. Therefore, it was insulated from the inside with timber battens, polyisocyanurate board, and phenolic foam. The wall was insulated with 82.5 mm thermal board and windows were replaced with double-glazed argon filled low e-coating windows where possible, and where they could not be replaced, the second glazing was installed to the existing ones. The old floor-mounted boiler was replaced with a new energy-efficient one as well. As a result of the retrofit, the total space heating energy consumption was reduced by 82%, which allowed for 750£ savings per year.

2.7 Chinese examples of building retrofit

2.7.1 Overview of policies, targets and benchmarks

The first policies in China addressing the issues of building energy demand and pressing the need to decrease it were developed in late 90s and beginning of 2000s. Thus, the 10th Five Year Plan (FYP) established an objective to install heat meters in residential buildings with centralised heating in large and medium-sized cities. At the same time, the first building energy efficiency standard for HSCW climate zone JGJ134-2001 (Ministry of Construction of PRC, 2001) outlined the improvement of building design to reach 50% reductions of building energy demand compared to the energy consumption of the Reference Building. The Reference Building used for this comparison was taken as the most common residential building from central China built between 1980s and 1990s. The standard also proposed benchmarks for annual heating and cooling energy demand, which depended on the building's local climate, specifically heating degree days (HDD) and cooling degree days (CDD). For the calculations the standard required to assume 24 hour operational heating and cooling with winter design temperature being 18° C and summer design temperature of 26° C. Thus, taking into account that HDD18 of Ningbo was 1375°C*d and CDD26 was 319°C*d in 2021, the EUI benchmark for heating would be 24.5 kWh/m^2 and EUI benchmark for cooling would be 34.2 kWh/m^2.

The next FYPs more specifically addressed building retrofit and renovation with aim to improve the energy performance in buildings. Thus, during the period of 11th FYP the government provided 24.4 billion CNY (Chinese Yuan) to retrofit 182 million m^2 of both residential and public buildings. 12th FYP covered greater floor area providing different requirements for different climate zones while focusing on the northern parts of the country as the main energy consumer. The targets were to retrofit 400 million m^2 of residential buildings in the north, 50 million m^2 of residential buildings in HSCW, and 60 million m^2 of public buildings. 13th FYP proposed greater target of 500 million m^2 of residential and 100 million m^2 of public building area retrofitted across the country.

Simultaneously, regulation-based policies affecting the new built were made more stringent. Recent local building design standard DB33/1015-2015 (Ministry of Construction of Zhejiang, 2015) imposed stricter regulations on building envelope and equipment performance aiming to achieve a design target of 65% energy saving compared to that of the Reference Building. In addition to this, a new technical standard for nearly zero energy buildings was developed and published in 2019 proposing the design of ultra-low energy buildings with energy consumption reductions of 75% (MoHURD, 2019). These improvements should encourage the construction of new more energy efficient buildings and subsequently reduce the carbon emissions of building sector. However, to achieve the 60-65% decreases (compared to 2005 level) of CO_2 emissions per unit of GDP by 2030 established by the Chinese government (Department of Climate Change, 2015) much greater energy reductions would be required. According to Jiang (2016), THUBERC

(2013) and THUBERC (2016) to achieve this goal, the annual heating and cooling in HSCW climate zone must be limited to 20 kWh/m^2, which would require improvement of both the new and the existing building stock.

In addition to these direction-based and regulation-based policies, China also implements various national information distribution, professional training, building evaluation, and financial support policies such as pilot projects, participating in Sino-German Technical Cooperation "Chinese Energy Efficiency in Existing Buildings" project, development of its own building assessment standard, subsidies and decreased taxes provided by both national and local funds (Liu et al., 2020a).

2.7.2 C40 China Building Programme

To promote the emissions reduction targets and energy efficiency, some Chinese cities are implementing additional building energy programmes and policies. The four pioneering cities presented in C40 China Buildings Programme: Launch Report (Sherlock et al., 2018) are Beijing, Shanghai (Changning District), Qingdao and Fuzhou. The main target in this programme for Beijing is to construct new ultra-low energy efficiency buildings through the creation and refinement of innovative design standards, and based on the pilot 300,000 m^2 of building projects provide training and support to other cities. Shanghai's Changning district is focused on retrofitting existing buildings instead of building new ones, giving the priority to commercial and public buildings. Fuzhou is a pilot city to integrate renewable energy (solar thermal hot water, heat pump, PV panels, etc.) technologies into commercial, public, and residential buildings. In Qingdao, the program is concerned with the improvement of residential buildings' envelope thermal performance for both energy efficiency and occupants comfort purposes. It also reviews the financial stability of building retrofit actions.

Since in Beijing the focus is on new construction and in Shanghai on public and commercial buildings, further discussion of the C40 programme in those cities brings little value for this research. Thus, only Fuzhou and Qingdao will be reviewed more closely below.

2.7.2.1 Fuzhou

The renewable energy installation projects in Fuzhou city cover residential, public and commercial buildings. The most widely spread in the city renewable technologies are SHW systems, various heat pump systems, and solar PV panels. This choice is largely directed by the city location: being located in the hot summer warm winter coastal region, it has a considerable amount of solar energy and water resources both of which can be used to keep the indoor environment cool in hot summers or to generate electricity. The city government made the installation of centralised solar hot water systems for residential buildings below 12 floors mandate.

Though the climate in the HSCW zone is colder than in Fuzhou, Ningbo city might also benefit from the installation of solar renewable technologies. Thus, it is suggested to evaluate the financial, energy, and environmental characteristics of SHW and PV panels' integration into the building. As for the heat pump systems, their installation is more complex, which usually results in a high initial cost. In addition to that, cold winter temperatures that occasionally fall below freezing point make it impractical and even dangerous to use ground source heat pump air conditioning systems.

2.7.2.2 Qingdao

Between 2016 and 2018 there were 136,000 apartments retrofitted in Qingdao with plans to continue prioritising existing buildings and improving their energy efficiency and indoor environment conditions. Starting with the 12th Five-Year Plan the government proposed a central policy priority that aimed at decreasing the total residential sector energy demand. Both central and local subsidies were featured to stimulate the retrofitting market. A 'comprehensive heating retrofit' included adding insulation materials on building envelope elements, improving building airtightness, window and door replacement with energy-efficient alternatives, and installation of heat meters and thermal control. These interventions were found to reduce the heating energy demand by 40%, save 150,000 tons of CO_2 emissions, raise the indoor temperatures by 3-5 °C, and improve air quality and public health.

A review and analysis of similar retrofitting measures and their economic and environmental performance are proposed to be done for Ningbo city. The introduction of additional insulation is expected to result in heating energy demand decrease, while installation of energy-efficient Low-E windows could decrease energy consumption in both winter and summer. However, installation of heat meters and thermal control like it was done in Qingdao is impossible in Ningbo, since according to Thermal Design Code in Civil Buildings (MoHURD, 1993) this area has no central heating.

2.7.3 Public perception of retrofits in China

Previous research has shown that the overall refurbishment rate and its success depends on both the government and public actions and active participation and cooperation of the two sides (Johnson et al., 2021, Liu et al., 2021, Long et al., 2015). Since the primary objectives of both the government and building residents during any building retrofit activity are to extend the service life of the building and decrease the annual energy consumption through the improvement of energy performance, the two parties should work together to achieve the goal. In projects where residents were engaged in the decision-making process and could decide what retrofit technologies were to be installed, the final satisfaction with the product was much higher (Glad, 2012, Xu et al., 2013, Chu et al., 2009, Liu et al., 2021, Long et al., 2015). The financial co-investment of the residents into the project was also connected to the observed higher involvement and interest to understand the newly installed technologies lead by the financial incentives and consequently feeling of ownership over the new equipment or design (Johnson et al., 2021, Abreu et al., 2017). On contrary, in projects that did not involve the residents in their decision-making process nor asked for their opinion regarding any of the implemented measures, unsatisfied residents either did not interact with new systems or demolished the new infrastructure. This is a waste of finances, energy, and resources that must be avoided in residential building retrofits.

Residential building retrofitting projects in China are usually performed in a top-down manner with government policies being the main driving force (Liu et al., 2015, Yan et al., 2011). This leads to the occupants' participation often being neglected in the process and the possibility of residents' initiation of any building retrofits not being considered. In addition to that, the risk of retrofit underperforming is high in this scenario. Thus, to achieve optimal results, the households must know, understand, and accept the new energy-saving technologies, and better yet, directly participate in their installation.

With their strategic city reconstruction plans, the local and national governments usually outline retrofit considerations and aim years ahead covering large macro-scale residential areas. This planning involves great time and financial investments that the common residents often do not possess. Understanding the main reasons for agreeing to or initiating building retrofits by occupants is important to provide them with the most valuable and best-suited evidence of retrofits' results. According to (Liu et al., 2015) in China, the residents display little concern with the energy-saving or sustainable side of the building retrofits. For many occupants, the questions of improved indoor environment quality, raised quality of life, and decreased energy bills were of higher importance than protecting the environment.

Thus, it is important to provide building occupants with retrofit options for their living spaces that could be performed all at once or one by one depending on the residents' preferences. Additionally, the financial concerns of building retrofit measures should be given higher priority than the environmental ones to provide the residents (potential retrofit participants) with attractive and simple incentives to initiate the retrofits.

2.8 Building retrofit measures overview

Considering various building retrofit measures implemented in the reviewed literature, they can be classified based on the building services systems they involve and how they perform (Traynor, 2019, Nick, 2010, Douglas, 2006). The majority of building retrofit measures are focused on reducing the energy consumption of the building (Figure 2.3). These measures can affect both passive and active building services systems. Passive building services are the ones that require no mechanical or electrical systems. Passive energy reducing building retrofit measures include additional insulation on building envelope elements (walls, roofs, floors, and ceilings), installation of energy-efficient windows and doors, improvement of thermal integrity of the building envelope through the elimination of thermal bridging and unnecessary infiltration, or building form improvements directed towards passive cooling and heating (shading, natural ventilation, thermal mass, etc.). Active energy reducing building retrofit measures direct active building systems and improve their performance such as upgrading the domestic hot water (DHW) system, installing new energy-efficient heating, cooling and lighting. The energy-producing group of building retrofits is focused on on-site thermal and electrical energy generation. Usually, this group includes SHW installation (flat plate collector or evaluated tube collector), PV panels (monocrystalline, polycrystalline), various geothermal systems and wind turbines.

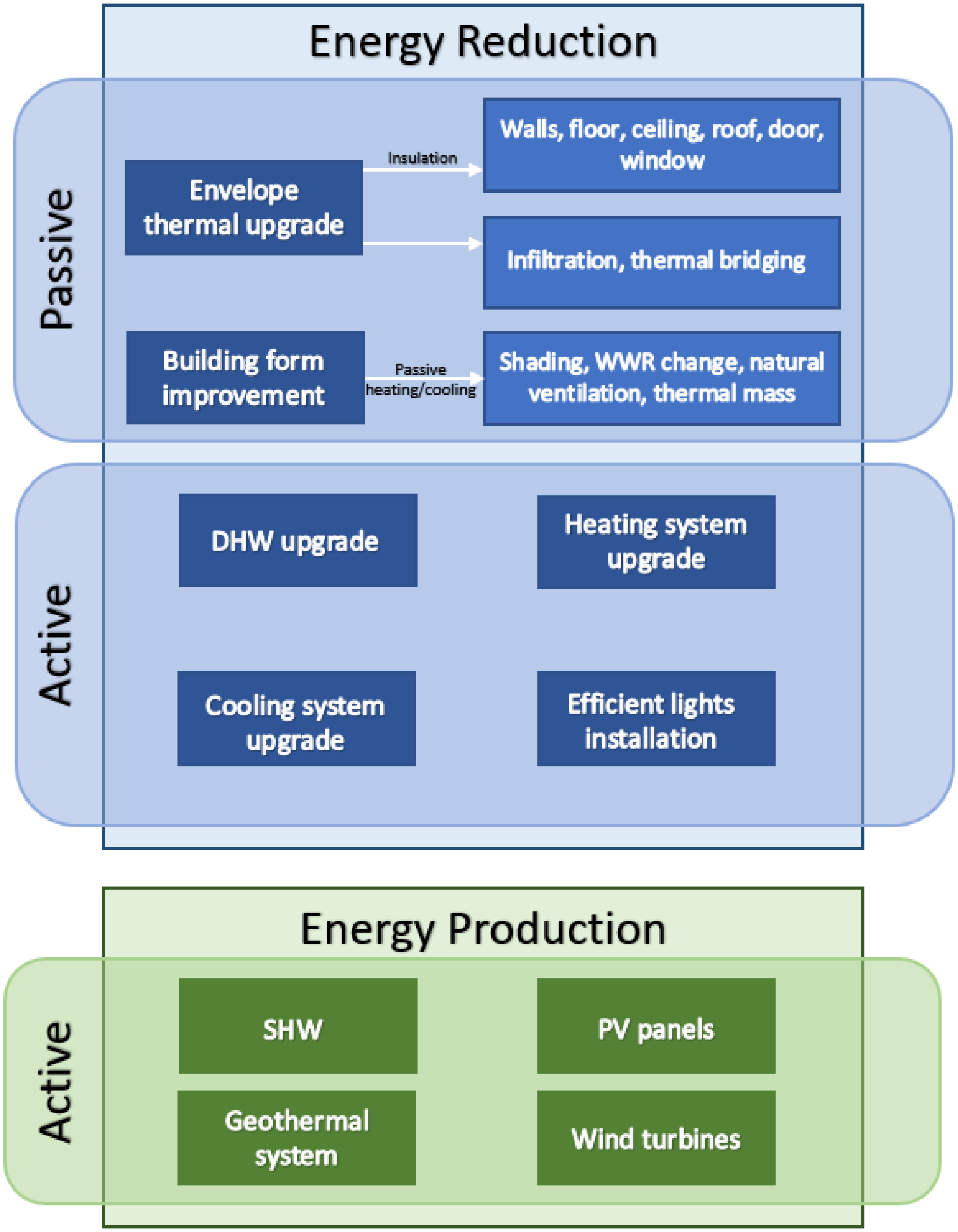


Figure 2.3 Building retrofit measures classification

2.8.1 Building envelope upgrade

Building envelope protects the building against external environments. The energy is continuously being transferred between the comfortable indoors and uncomfortable outdoors one way or the other. Therefore, improving this protection would decrease the material surface temperature fluctuations and reduce the heat transfer allowing to rely less on the active temperature-maintaining building systems such as heating, cooling, or air conditioning.

Upgrading building envelope elements such as walls, floors, roof, windows, and doors is common in building retrofit research and has been proven to be an effective energy saving measure (Shah, 2012, Riley, 2011, Burton, 2012, Danish Government, 2014, Ardente et al., 2011, Parker, 2010). In addition to this, highly insulated envelope is essential for passive houses and a very important consideration in nZEB design and retrofit, and thus must be considered when improving energy performance of a building.

However, the exact performance of building envelope insulation depends on the local climate and initial state of the building materials. According to (Ardente et al., 2011) in northern European countries additional insulation can reduce heating energy consumption by 10-25%, while in some cases even up to 45% of heating demand. Considering the environmental impact of these changes when counting the gross energy required to produce the materials against avoided carbon dioxide emissions driven by energy consumption decrease, $500*10^3$ – $2000*10^3$ $kgCO_{2eq}$ can be saved in public buildings. In northern China's climate similar energy savings have been calculated in buildings after retrofit: with additional 70mm of EPS insulation and replaced windows and doors the average energy demand reductions were 15.6% (Xin et al., 2018).

While evaluating building retrofit scenarios for China's Temperate and HSCW climate zones, (He et al., 2021b) stated that wall and window insulation are the primary measures for optimal retrofit. Installation of 30 mm EPS insulation on walls and replacement of windows to efficient low-e double glazed ones in conjunction with other retrofit measures allowed to achieve 30% decreases in total energy consumption in Temperate zone and up to 40% in HSCW climate zone. Liu et al. (2020b) studied the influence of additional wall insulation on buildings energy demand with different AC operational modes in HSCW zone and found 7% reductions with 150 mm of EPS in continuous mode and 9% for intermittent operation mode. In hot and arid climate like Kuwait replacing single-glaze windows with low-e double glazed and adding 50mm of extruded polystyrene to the wall and 75mm to the roof decreased the total building energy consumption by 38% (Al-Ragom, 2003). Cheung et al. (2005) found that between 20% and 30% savings in cooling energy demand can be achieved installing 100 mm of insulation inside and outside the wall. Nonetheless, in hot climates additional care must be taken since excessive insulation especially on the roof might increase building cooling energy demand (Pan et al., 2012).

The main drawbacks of adding insulation to existing building structures are high initial investment costs and long payback periods (Fan and Xia, 2018). Thus, in a set of optimal retrofit options for HSCW zone to achieve 40% energy reductions target wall insulation costs accounted for almost 35% of total initial investments (1130 USD per apartment) while windows accounted for 30% (960 USD per apartment) (He et al., 2021b). Yu et al. (2009b) reviewed different insulation materials (XPS, EPS, perlite, foamed polyurethane, foamed polyvinyl chloride) and found EPS being most cost-effective for Shanghai climate with 35.4–54.4 $\$/m^2$ life cycle savings during the 20 years lifetime. According to Al-Ragom (2003) 20,768 USD were required to retrofit building envelope elements of a two-storey residential building which resulted in a payback period being 50 years – a period too long to justify the investments for end users. This emphasizes the importance of policies and subsidies to support building retrofits and make them more financially attractive to the public.

2.8.2 Shading

Historically, windows were made small to minimise the solar heat gain in summer and heat escape in winter while still allowing light in and view out. Nowadays, windows have become bigger to please the aesthetic views, which results in increased building energy demand (Shah, 2012). This issue may be addressed with shading devices and according to Shah (2012) there are four approaches to shading all of which have different advantages and disadvantages: external (include overhangs, blinds, louvres, and fins), internal (venetian blinds or roller blinds), inter-pane, integrated (light-shelves and prismatic systems). Exterior overhang can be further divided into vertical and horizontal; horizontal is usually situated slightly above the window and its shape, depth, and height depend on the local solar conditions; vertical shading is usually used on eastern and western facades and in addition to shading the window it can also act as a windbreak (Shaikh et al., 2017). The most common of aforementioned types and the ones that are most often evaluated in a retrofit scenario cases for their ease of integration in pre-existing design are internal and external shades.

Typically, the internal shades are easier and cheaper to install and they can be used for blocking solar heat gains and minimising the effects of glare, they can also be easily adjusted by occupants throughout the day to accommodate to their immediate needs. Meanwhile, the external shades are subjects to weather damage and dirt build-up, they require larger financial investment for their initial and maintenance costs and are difficult to adjust. However, internal shades let the solar heat enter the indoors and trap it inside increasing the temperature and some research states increase cooling energy demands. Thus, Atzeri et al. (2014) evaluated roller shades on the inside and outside comparing the thermal and visual environment and energy consumption. Both internal and external shading devices increase lighting electricity demand almost equally. However, they have different effects on heating and cooling energy demand: external rollers decrease the cooling demand and slightly increase the heating, while internal shades strongly increase cooling and slightly decrease heating which makes external shading devices a much better choice. In Ye et al. (2016) similar results were obtained with external shading devices outperforming the internal ones: 13.81% compared to 4.36% cooling energy demand decreases respectively. However, the authors claim that with optimisation of shading's solar transmittance, reflectivity, distance between shading device and window, etc., the performance of internal shading devices can be improved to the levels of external ones.

Nonetheless, window shading devices have been shown to improve both internal environment and building energy performance. According to Corgnati et al. (2017) occupant adjustments of external shading devices accounted for 6-13% of total variation in building energy consumption driven by occupant behaviour. In hot and sunny climate that is in western Africa, cooling energy reductions achieved with shading can be up to 40% with external shutters showing the best performance (Ouedraogo et al., 2012). In Brazil, the use of external aluminium shutter decreased cooling consumption by 34% and use of wooden shutter by 36% (Invidiata and Ghisi, 2016). These operational energy savings greatly exceeded the shadings' embodied energy, maintenance energy, and demolishing energy combined which emphasised their benefit for the environment and consequently highlighted the need to include shading devices into the list of evaluated retrofit measures. Evaluating the most cost-optimal retrofit solutions for HSCW zone, (He et al., 2021b) also included shading into the proposed set of best measures.

2.8.3 Active equipment upgrade

Over 60% of total building energy demand worldwide comes from thermal uses (Ürge-Vorsatz et al., 2015). Thus, upgrading heating, cooling, and DHW systems would extensively contribute towards reductions in building energy consumption. The selection of suitable type of systems during a retrofit would depend on many factors such as building type, existing systems and available equipment, available space, climate, financial restrains, etc. Thus, in hot tropical climates heating is not required, therefore the consideration should evolve around cooling system and DHW systems. If SHW is installed, it could be considered to use the hot water for cooling too. In temperate and cold climates, however, it is common to use the same equipment (boiler) for both heating and DHW purposes, while cooling (until recent increase in temperatures driven by climate change) was not used in many places.

The most commonly reviewed residential heating options are central heating, furnace, boiler, heat pump, underfloor heating, ductless mini-splits, SHW, and radiant heating. Some of these systems are used in combination with each other, e.g. underfloor heating can be electrical or water-based connected to either a boiler or central heating, heat pump can be used as a pre-heat for the boiler, etc. During a retrofit, Shah (2012) suggests following energy-efficiency measures for heating systems: minimisation of number, and location, of plantrooms to reduce potential losses; reliable and accurate space-heating controls; insulation of distribution systems; heat recovery for space heating and pre-heating of domestic hot water.

Considering the improvement of existing system without replacing it for a new type, the equipment and distribution system can be upgraded. Thus, improving central heating system carbon dioxide reductions (up to 25%) and financial savings (with payback period of 0.5-2 years) can be achieved by insulating the district heating pipelines (Başoğul and Keçebaş, 2011, Ucar, 2018, Kayfeci, 2014) or domestic heating pipelines (Hamburg et al., 2021, Küçüktopcu et al., 2022, Bøhm, 2013). The same strategy can be applied to radiant heating, SHW, and other DHW pipes. Considering the retrofit or replacement of different types of boilers, care must be taken to verify the availability of fuel types and the economic and environmental consequences of its production and delivery on site (gas, oil, electricity, biofuel). The environmental footprint of electrical boilers can be location dependent more than others, since it would depend on the fuel used at the power plant (coal plant's emissions would drastically surpass that of a wind farm (Rogers et al., 2008). One of the advantages of heat pumps is that it can provide both heating and cooling (Smith, 2004). Ground source heat pumps are the most efficient ones, but they require substantial amount of space on the site for underground heat exchanger and therefore are very expensive to install. According to Smith (2004) they can be two to three times more expensive than the conventional fossil fuel boilers. The cheapest version of heat pumps is air-to-air heat pump, which are very common in climates with mild winter and hot summer.

Comparing different system types, Sigrist et al. (2019) evaluated the economic and environmental performance of oil boiler, geothermal heat pump, ait-to-water (indoor and outdoor types) heat pumps, district heating, SHW, and pellet boiler to cover the heating and DHW supply demand of a Swiss single-family house. Based on their research, the most economically and environmentally beneficial option was the geothermal heat pump, which had very high initial cost that was offset by very low operation, maintenance, and energy costs as well as long lifetime. Both types of air-to-water heat pumps and SHW displayed relatively similar results that were worse than the geothermal heat pump, but better than district heating and pellet boiler. Switching from a conventional DHW system to a renewable one “leads to enormous savings in GHG emissions”, even when no other retrofit measures are implemented (Sigrist et al., 2019).

Among the residential cooling equipment the common options are central air conditioning, heat pumps, ductless split AC, and evaporative coolers (McMullan, 2017). Similarly to the heating system, the selection of these options would depend on many local factors beyond the economic and environmental considerations such as existing equipment, available space, etc. Both heat pumps and central air conditioning require air ducts to distribute the cool air around the house. In addition to that, they cool down the whole house and do not present room-to-room flexibility, increasing the total cooling energy demand (Smith, 2004). Evaporative coolers push the outside air through moist membranes cooling it down via evaporation. This type of cooling system works best in dry climates, its costs can be a half of that of central AC and they can be 75% more efficient.

Nonetheless, improvement of each system is possible and could bring both economic and environmental benefits with it. According to Akgüç and Yılmaz (2022), advanced retrofit of air conditioning system can decrease the annual energy consumption by 39% in high-rise buildings. (He et al., 2021b) suggests installation of a more energy efficient air conditioning system in HSCW climate zone of China as one of the optimal retrofit measures to achieve 30% and 40% energy demand reductions.

2.8.4 Lighting replacement

The benefits of retrofitting lighting include the reduction of energy demand required to maintain adequate illuminance levels, decrease bills, improve visual comfort, and in addition to that, it can reduce the cooling requirements and maintain more comfortable temperature in summer (Shah, 2012). It is one of the cheapest retrofit measures that can be easily implemented regardless of the retrofit designs and plans. Replacing halogen light bulbs with efficient LED light can result in up to 90% energy savings while maintaining the same illuminance levels (Shah, 2012, Frascarolo et al., 2014). Moreover, according to Tähkämö (2013), the life stage of different light sources that contributes most towards the associated emissions generation is the use stage, which is very sensitive to the efficiency and service life. LED lights outperform halogen, fluorescent, and incandescent lights in both of these parameters, presenting the lowest lifecycle emissions (Tähkämö, 2013). While in residential buildings lighting contributes to a small percentage of total building energy consumption and thus its improvement is not as noticeable as other retrofit measures, its low costs (around 40 USD per apartment according to He et al. (2021b) make it an option suggested by many researchers (He et al., 2021b, Frascarolo et al., 2014, Onyenokporo and Ochedi, 2019, Kuhn et al., 2013, Tan et al., 2018).

2.8.5 Renewable Energy production

The main advantage of using on-site energy production technologies is the minimised transportation losses. They can be installed in the building or building site and cover a single building or in the local community and cover several buildings. The most common types of on-site renewable energy production are PV panels, SHW, geothermal, and wind turbines. These technologies can be used to provide heating, cooling, and/or electricity.

The geothermal systems can be shallow (such as heat pumps discussed in Section 2.8.3 as one of the commonly evaluated heating / cooling systems), deep (up to 5 km deep), or medium-deep. The last two are used on a central scale, while the first one can be a community or a building scale. In building retrofit, shallow geothermal systems present beneficial economic and environmental results, but they are hindered by their high initial cost and location dependency (Romanov and Leiss, 2022, Pratiwi and Trutnevyte, 2022).

The SHW collectors' can be flat plate and vacuum tube collector. While flat plate collectors are much cheaper than the vacuum tube type, their efficiency is much lower and they often do not provide temperatures commonly used in heating (above 60°C). However, they can be used in solar thermal hybrid systems as preheaters that are connected to the boiler. According to Smith (2004), SHW is one of the cheapest renewable source of energy.

Commonly used PV panels are monocrystalline and polycrystalline types. The average efficiency of PV panels is between 15% and 25% with monocrystalline panels showing higher performance than the polycrystalline. According to Akgüç and Yılmaz (2022), the integration of PV panels into high-rise buildings allowed for energy demand decreases of 50%. Albadry et al. (2017) states that buildings in Egypt can be converted to nZEB with installation of PV panels under an affordable price. In other research done by Sun et al. (2019) it was found that in Glasgow the payback period of a PV system was 5.1 years, an integrated PV and SHW system – 3.56 years and that of a hybrid PV thermal system – 3.62 years. Both PV and SHW systems work from solar irradiation and thus they display high performance in locations near the equator, however, successful and beneficial integration in other locations are also common. Rehman et al. (2020) studied the integration of PV panels, geothermal heat pump, and air-to-water heat pump to substitute the central heating for residential building communities in Finland. Their results have shown that with installation of all three equipment types the relative reduction of emissions was 83% while simultaneously the LCC decreased from 339 €/m^2 to 277 €/m^2 for original reference buildings. In deep renovated buildings the environmental and economic benefits were smaller and the geothermal heat pump is not recommended as the energy cost decreases could not cover its initial cost.

Energy production by wind is rarely used in urban areas due to the wake effect created by nearby buildings – turbulent slowed down wind that does not provide the same kinetic energy as the undisturbed uniform high speed winds in rural areas. Therefore, wind turbines struggle to perform competitively when compared to other forms of energy in urban areas. Sunderland et al. (2016), Bukala et al. (2015), and Pellegrini et al. (2021) estimated that the initial investment cost of a wind turbine is too high to be justified in urban environment. Using LCA, Wang and Teah (2017) found that under the wind conditions of Tainan in Taiwan it is not environmentally beneficial to install small-scale wind turbines and that it would require 160 years to offset the emissions generated by production, construction, and disposal.

The main economical drawback of all of these systems is high initial cost. As for the environmental consideration, both PV panels and wind turbine blades are difficult to recycle and it is cheaper to landfill them than to recycle and thus their end-of-life footprint is relatively high (DOE, 2022, Chowdhury et al., 2020, Fonte and Xydis, 2021, Paulsen and Enevoldsen, 2021). SHW, especially the flat plate type, does not present these challenges.

2.9 Conclusion

To achieve sustainability globally and in the building sector, it is essential to have a sound understanding of various environmental impacts and how they can be addressed through building stock improvements.

This chapter reviewed the definition of sustainability and discussed the environmental issues implicated in sustainable development. Drivers for sustainable development in China specifically as the largest energy consumer in the world were presented. This information was important to gain a deeper understanding of environmental problems in China and what sustainability practices need to be applied to building stock to address the environmental crisis.

Here, it was argued that building retrofits are a sustainable way to improve the quality of existing residential building stock and decrease future energy consumption. Comparing retrofits to new construction, they require fewer materials and other resources. Thus, an overview of data required to manage, maintain and retrofit buildings was provided. This highlighted the types of data that must be collected and analysed to execute this research. International and local examples of retrofit installation were reviewed and discussed. From these real-life examples of retrofit, suggested building retrofit measures were drawn to be applied to China’s residential building stock for evaluation purposes.

Based on all the discussed points, the research aim of proposing sustainable and suitable retrofitting methods for China’s residential building stock was established. The review of the information required to perform this research also guided the generation of research objectives.

3 Chapter 3. Literature Review

3.1 Introduction

In 2018 the total building energy demand in China was 1123 Mtce with the urban and rural residential sector contributing to almost a half of this amount (Jiang et al., 2018, Guo et al., 2021). Improving the energy efficiency of existing residential buildings is essential for China to mitigate the effects of environmental pollution and thus contribute to the mitigation of climate change. To achieve that, reliable methods must be developed to estimate the effects different building retrofit measures pose on energy consumption. Additionally, these effects must be assessed and compared for the selection of the best retrofitting option.

Thus, this chapter discusses approaches and methods present in other scientific research directed towards building retrofits. This step is imperative for establishing a methodology for this thesis that would help to achieve the set aim and objectives. Methods to collect data on residential building stock and analyse it are discussed. To better identify existing methods to predict the influence of different retrofits on residential building stock literature review is performed. Moreover, current methods to assess and quantify the economic and environmental influence of retrofits are discussed here too.

3.2 Residential building stock energy simulation

According to Li et al. (2017), there are two methods to perform city building stock energy simulation: top-down and bottom-up. The top-down approach considers many buildings as a single unit with its energy demand without distinguishing among the buildings. The prediction of future energy consumption is made based on the previous trend of interaction between energy demand and different socio-economic variables. The main advantage of this approach is that the specific technology description is not required, making the model relatively straightforward and simple. However, the main disadvantage is the need for long-term historical data and the lack of technological details. In addition to that, the lack of technical specifications makes it impossible to use these models for specific retrofit measures evaluations.

The bottom-up approach is further divided into statistical analysis and physics-based models. Statistical analysis is similar to the top-down method in a way that it uses historical data and socioeconomic factors. However, the data is gathered not on a building unit level but for single buildings, making the variations in individual end-users possible to distinguish. Since the disadvantages of this method are the same as for the top-down approach, it is not suitable for this research.

The physics-based model performs simulation based on a single building's physical parameters such as building envelope, heating and cooling systems, HVAC system, occupancy patterns, etc. It provides higher simulation accuracy and a possibility to perform simulation at different scales and for different purposes. The main drawbacks of physics-based models are that they require more technological building-specific data and higher computational effort than statistical analysis. Nevertheless, implementation of physics-based models in this research is essential to achieving set in Chapter 1 targets.

Building energy demand heavily relies on many different parameters and characteristics associated with the shape of the building, its fabric, operational equipment, usage schedule and weather conditions. However, the availability of this data is very limited. Moreover, when aiming at representing the whole city's residential building stock, it is not feasible to first collect data for each building and then model each of them for further simulation due to the high diversity of residential buildings and their enormous number presented on a city scale. An alternative method present in the literature is to identify a typical set of building characteristics or inputs for each significant variation of the residential stock and based on that develop building typologies representing a group of similar buildings that would allow both adequate model accuracy and practicality. From these building typologies, reference buildings can be modelled for detailed energy consumption evaluation allowing for analysis of potential changes and different retrofit scenarios. They can enhance the overall understanding of energy flows in buildings and guide the policy makers.

3.3 Building typologies and reference buildings

Research on typologies is concerned with the common typical characteristics of the elements and their classification (Pfeifer and Brauneck, 2015). It can be applied to many fields of science and disciplines. From the architectural perspective, it is usually used to study the characteristics of the building form or function. Based on these results, typical groups of buildings are established. While the typology in itself is more of a data analysis process, the outcomes of that process are buildings representative of each typology.

The Commission Delegated Regulations describe two ways to define reference buildings: selecting a real example building and creating a virtual building (European Commission, 2012). Establishing the reference building using the first method requires statistical analysis of a large amount of detailed data on the building stock to select a real building with close to average characteristics compared with other buildings in the sample. Creating a virtual building can be done either based on expert knowledge, such as standards, codes, handbooks, manuals, etc. or based on the results of statistical manipulation of the analysed samples (Brandão de Vasconcelos et al., 2015, Corgnati et al., 2013). These methods are presented in Figure 3.1. In many cases, the virtual building is modelled using both of these sources of data.

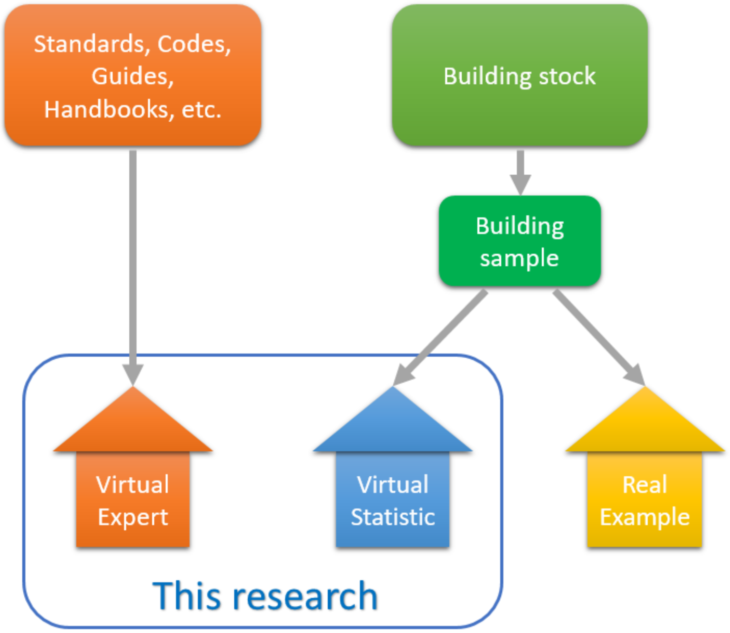


Figure 3.1.Reference building definition methods

In the scientific literature, the scale of the building typologies analysis varies from regional to national level and the number of the created typologies as well as their complexity is different for different research. Thus, Monteiro et al. (2017) took a Lisbon residential neighbourhood as a case study and developed a single residential building prototype first with the climate being the initial parameter. They further considered construction period, size class, roof type and neighbouring as the input parameters increasing the complexity of their models and the number of typologies developing 18 reference buildings. Using statistical analysis to establish the most significant classes of residential houses, Famuyibo et al. (2012) modelled a national Irish domestic dwellings stock creating 13 building typologies. In Brandão de Vasconcelos et al. (2015) the authors combined data from the expert knowledge sources and the statistical data for the development of the most representative residential apartment block (multi-family building) constructed between 1961 and 1990 in Lisbon, Portugal. The data were collected from two Portuguese databases namely Portuguese Statistical Institute (INE) and Portuguese Energy Agency (ADENE). Mata et al. (2014) provide an overview of the residential and non-residential building typologies development in France, Germany, Spain and the UK. The presented methodology consists of four steps: segmentation, characterization, quantification and validation. A reduced-order building energy model with an EPC calculator was used to simulate Manhattan city's energy demand (Li et al., 2015). It has 16 building typologies derived from the DOE data and ASHRAE standards with the building construction period specified as pre-1980, post-1980 and new construction pre-2004.

One of the biggest building typology libraries is developed under the Typology Approach for Building Stock Energy Assessment (TABULA) research (TABULA, 2012). It combines the residential building data of 13 participating countries taking into account three main independent variables namely: location, age and geometry. In Ballarini et al. (2014) the analysis of Italian residential building stock in the Piedmont region and development of building typologies are presented as a part of the TABULA project. Six Building Age Classes and three Building Size Classes were developed creating a Building Typology Matrix. Each cell of the matrix describes one building type from which a reference building (either a real example building or a synthetically average building) was created. The mean seasonal efficiencies of the DHW system and the heating system (both distribution and generation) are derived from Technical Specification standard, which defines it as a function of the building age and type. 18 building typologies were developed. The development of Danish building typologies financed by TABULA and reported by Kragh and Wittchen (2014) was done combining data from two main building databases in Denmark: Energy Performance Certificate (EPC) Scheme and The Building Stock Register. The first one had approximately 540,000 valid EPC at the end of 2016, which accounts for a third of the total residential building stock; while the second database contains all 1.6 million buildings. The building types were divided into three groups: Single-family, terraced houses and blocks of flats each with 9 different construction periods. As the reference buildings, real example buildings provided by EPC were chosen and average building models were developed. To estimate the U-values of the building envelope components, the area-weight numbers were calculated.

Research done by Filogamo et al. (2014) analyses the residential building stock of Sicily Island using the statistical data on 1,717,000 dwellings provided by the Italian Institution for Statistical Analysis (ISTAT). The methodology for building typologies development proposed by the authors consists of five steps. The first step divides the building stock by construction period, the number of floors and the number of dwellings. In the second step, the average building shape coefficient of each cluster is calculated. The third step assigned thermo-physical properties to the building envelope depending on the year of construction as well as the window to wall ratio (WWR) being 30%. During the fourth step, a survey on heating appliances was developed that revealed 9 heating system types with the number of appliances in each dwelling being dependent on the average users' income. The last step located the sample buildings in different climatic zones. Thus, winter heating was calculated by applying ISO 13790, cooling, lighting and appliances energy demand was estimated by the mean percentage per dwelling corrected based on users' income, and cooking and hot water energy were taken on average per year. The results revealed around 8% difference between the estimated energy consumption values (1193 ktoe) and the real ones (1100 ktoe).

In Cerezo et al. (2015) the authors evaluate and compare the simulation results of three methods to create typologies that have diverse levels of details: in Method A they simulated all buildings performing the same function (such as office, residential, etc.) as one typology with characteristics taken from a review of literature; in Method B the residential buildings are further divided into four groups based on the year of construction with parameters coming from local standards and construction codes; in Method C a probability distribution is assigned to occupancy related parameters such as lighting, plug loads, set point temperatures and the schedule. While increasing the level of details required a larger amount of information, it resulted in a higher level of accuracy and smaller variation and uncertainties of results. Monteiro et al. (2017) showed that the necessity of introducing a certain parameter into the building typologies depends on the variability of this parameter presented in the sample. The results revealed that additional information about the buildings tends to slightly increase the simulated energy consumption. Thus, introducing the construction period into the model increased the total estimated energy demand by 11%, dividing it further by size-class almost had no effect giving 0.1% increase, grouping buildings by roof type added 1% to the total results and subdivision by neighbouring resulted in additional 2% of energy demand growth.

According to Corgnati et al. (2013), all building data necessary for reference building creation can be divided into four main categories: operation, system, form and envelope. “Operation” is defined by the building’s location, type and occupants behaviour; it describes the usage schedule, lighting densities, equipment, ventilation requirements, activities performed by habitants, users’ preferences, etc. “System” refers to cooling, heating and ventilation systems design, on-site energy generation systems and building control fixtures. Category “Form” consists of characteristics describing building shape: floor area, number of floors, height, orientation, shape coefficient, etc. The final group, “Envelope”, describes U-values, amount of glazing, internal mass. However, different parameters influence the results to a different extent, therefore it is possible to decrease the amount of detail, and consequently decrease the amount of required data, while still preserving the accuracy of the results by including into the simulation only the most influential parameters. Mosteiro-Romero et al. (2017) presented a sensitivity analysis of different building energy simulation input parameters for different seasons. To decrease the amount of data needed for the modelling as well as the time required for the simulation, the number of input parameters was eventually reduced from 23 down to 11, which still covered 90% of the observed effects on the demand. During the heating season, the most influential parameters were the thermal properties of the building envelope for all types of buildings (52%) and the air exchange rate (26%). For the cooling season, the predominant parameters were set-point temperature and window-to-wall ratio. Additionally, the buildings were analysed by their shape. Thus, for compact buildings the greatest effect came from the air exchange rate for heating; non-compact buildings' energy results relied heavily on the envelope parameters. During summer the predominant parameter was the set-point temperature for all building envelope types. These results match the ones presented in Famuyibo et al. (2012), where the authors implemented the linear regression analysis on 23 independent building variables choosing 9 the most influential ones. The analysis revealed that the most significant variation in results came from air change rate, heating system efficiency and dwelling type.

From the extensive literature review of randomly selected forty-nine papers (including those discussed above) searched using ‘typology’, ‘reference building’, ‘archetype’, and ‘prototype’ as keywords, it is found that the analysed building characteristics can be divided into two groups. The first group is the building characteristics used for the segregation of data for the creation of typologies. For TABULA projects in many countries, the segregation characteristics are building age, form (or building type), and local climate (TABULA, 2012). In Mata et al. (2014) it is building type, year of construction, heating system, and climate. Overall, most commonly segregation was performed based on the thermal performance of the building envelope elements (often predetermined by buildings’ age), building form (size, shape, building type, etc.), and in national studies with presence of different distinct climate types, climate. The second group of building characteristics used for creation of building typologies is the input parameters. They include all the other available information on the buildings such as heating and cooling systems types, COP, summer and winter indoor temperature, occupancy patterns, lighting and equipment densities, etc.

Reviewing the papers on residential building typologies creation in HSCW climate zone in China revealed a lack of such research. The two earlier conducted studies that analysed residential building stocks were focusing on determining the ‘standard’ or most common building type. Thus, in Li et al. (2019) Chongqing municipality’s residential building stock was analysed according to bottom-up engineering stock modelling approach to create one most common average building form with different envelope thermal integrities for various construction years. This built form was based on the individual household flat with five flat floor plans developed representing different types of families. Gui et al. (2018) used the construction year to aggregate the residential buildings of Hangzhou municipality to determine the standard buildings for each construction period. Based on these results two building shape forms were found: point and strip buildings. Six internal layouts were created for the point building form and five for the strip building form. Real example buildings were assigned as the ‘standard buildings’ for the most common combinations of these parameters. These buildings varied between 3 and 7 floors.

To fill the gap in the research stated above, this thesis proposes the development of residential building typologies for the HSCW zone and Ningbo municipality in particular.

For the development of such typologies, it is suggested to use building segregation characteristics similar to those used in TABULA research except for climate, because this research covers one climate zone. Thus, the proposed segregation characteristics are:

- Construction year
- Building form (number of floors, area, shape, WWR)

3.4 Multivariate data analysis

The need to analyse observed data has been present for many centuries. Information retrieved from various data is necessary for effective knowledge creation and management as well as decision making. Previously, the techniques available to do it were very limited, mostly presented by our cognitive data correlation and segmentation and extremely slow and time consuming manual calculations. Because of this, the theoretical knowledge about data analysis was many years ahead of the practice. Nowadays, the creation and development of computers allow performing quick and precise arithmetical and logical operations on large data scales. Methods, that were previously too complicated to be calculated by hand, can now be implemented using a personal desktop computer. With the increase of computational power new data analysis methods have been created, including those, that are capable of processing complex phenomena with many variables called multivariate models.

According to Hair (2010) "multivariate analysis refers to all statistical techniques that simultaneously analyse multiple measurements on individuals or objects under investigation". Some of these techniques present extensions of univariate and bivariate analysis, while others were specifically created for problems with more than two variables. The main purpose of any multivariate analysis is to identify complex relationships that are difficult to represent simply.

All multivariate techniques can be divided into two groups based on the relationship among the variables: dependence techniques and interdependence techniques. The main idea behind the dependence techniques is that one variable or a set of variables in the collected data is assigned to be a dependent variable and its changes should be explained or predicted by other variables. For the interdependence techniques, however, none of the variables or groups of variables is known to be dependent or independent. These considerations are important when selecting the appropriate technique for a specific data analysis, as well as the type of the available data: metric (quantitative) or nonmetric (qualitative).

3.4.1 Dependence techniques

The most commonly used dependence techniques include multiple regression, multiple discriminant analysis (MDA), canonical correlation, multivariate analysis of variance and covariance (MANOVA), conjoint analysis and structural equation modelling. These methods differ in the number of dependent variables and types of dependent and independent variables. Table 3.1 provides an overview of the differences among these techniques.

Multivariate Dependence Technique	Dependent Variables		Independent Variables
	Amount	Type	Type
Multiple regression	One	Metric	Any
MDA	One	Non-metric	Metric
Canonical correlation	Many	Metric	Metric
MANOVA	Many	Metric	Non-metric
Conjoint analysis	One	Any	Non-metric
Structural equation modelling	Many	Metric	Any

Table 3.1 Description of multivariate dependence techniques and their variables

Thus, multiple regression analysis is used when the analysis is focusing on one metric dependent variable and many independent ones influencing it. This analysis aims to be able to forecast the changes of the dependent variable when other variables are changed. If the research requires doing a series of separate multiple regression analyses simultaneously, structural equation modelling is applied. MDA is used with one non-metric dependent variable and metric independent variables; it divides the sample into groups based on the dependent variable and its known classes. It aims to understand differences among those groups and evaluate the probability that an object will belong to one of the groups. If the independent variables are non-metric and they all affect one variable of any type, conjoint analysis can be used. Canonical correlation compares several metric dependent with metric independent variables and finds a set of weights for these variables that would best represent the correlation between them. MANOVA is implemented to measure the effect that several categorical independent variables exert on two or more metric dependent.

3.4.2 Interdependence Techniques

As it was mentioned previously, interdependence techniques are applied, when it is unknown if the variables are dependent or independent. Therefore, the main goal of this type of data analysis is to determine the underlining structure of the variables and their relationships through simultaneous analysis of the whole data set. Commonly used interdependence techniques are factor analysis, correspondence analysis, multidimensional scaling, and cluster analysis.

Factor analysis, which includes principal component analysis and common factor analysis, observes the relationships among many variables and creates factors that are made to substitute several similar variables for simple data observation and information retrieval. As a result, the information is condensed to a more representable way with a smaller number of factors (or new variables) and minimum information loss. Multidimensional scaling (also known as perceptual mapping) measures the similarity of the objects and creates metric variables for the data, which can be used to create a graph or a table. Correspondence analysis is similar to multidimensional scaling, but it can work with non-metric attributes. It provides a multivariate representation of non-metric data and non-linear relationships that are not possible with other methods. Cluster analysis is used to segment the data into mutually exclusive internally similar and externally different groups without the predefined group characteristics.

3.4.3 Cluster analysis

The ability to put objects in categories to apply already known rules about similar objects on a new encountered one is present in all intelligent beings. It is essential for the survival of living creatures to be able to categorize things into ‘edible’, ‘poisonous’, ‘dangerous’ and other important groups. With the development of science, classification became an essential part of understanding and enhancing all branches of disciplines. Classification of plants and animals provided the ground for the development of Darwin’s theory of evolution. Categorization of elements based on their physical and chemical properties presented in Mendeleyev’s periodic table greatly increased our understanding of atoms and their interaction with each other. On every day’s basis classification is used for communication and language development as it helps us to name, recognise and discuss different types of objects, events and people using various words.

Depending on the application, categorization can be used to provide an efficient way of big data sets organization to improve the understanding of the data structure and characteristics as well as retrieve information from the data more conveniently and faster. It can also be used to forecast the possible characteristics of a newly discovered object or event. Since the same set of objects can belong to different groups based on a variety of alternative classification rules (fruits can be classified based on their colours, place they grow or taste), it is essential to create categorizations that would be useful for the specific task these groups are needed for.

Based on Everitt (2011), the numerical techniques implemented for classification largely come from natural sciences such as biology and zoology. With time, these methods have been integrated into other areas of sciences and have been given several names depending on the field of application. The most generic term that is used to describe the procedures of revealing groups in data and classifying objects into these groups is called cluster analysis. Hair (2010) defines cluster analysis as "an analytical technique for developing meaningful subgroups of individuals or objects", stating that the objective of it is "to classify the sample of entities (individuals or objects) into a small number of mutually exclusive groups based on the similarities among the entities". Unlike discriminant analysis or assignment method, when implementing cluster analysis the groups are not known.

The segmentation of data via cluster analysis should present results that have high homogeneity within the group and high external heterogeneity. The similarities of the objects or the individuals in the data can be assessed visually or mathematically (either manually or using a computer). The graphical analysis of multivariate data allows the visual evaluation of the data and the detection of possible clusters when using the direct method. Scatterplot is one of the useful techniques for determining clusters when there is a relatively small amount of variables available. Figure 3.2 shows a scatterplot with three easily identifiable by human eye clusters. Other methods of visual analysis of univariate, bivariate and three-dimensional plots of data include histograms, density estimation, scatterplot matrix and trellis graphics.

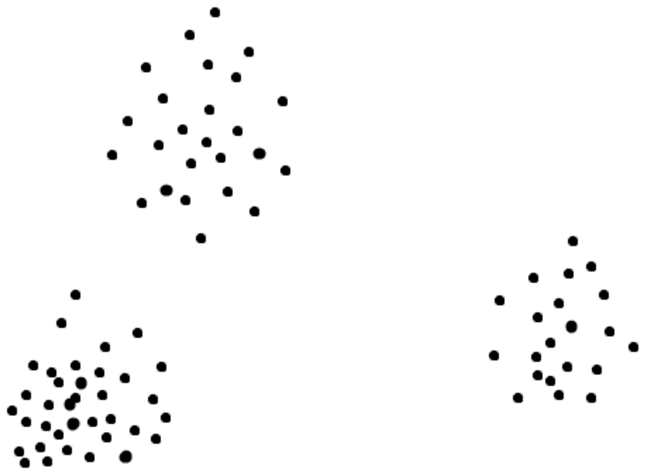


Figure 3.2. Scatterplot showing three distinct groups of points

If the data has multiple variables, visual identification of separate clusters might be problematic. Multiple dimensions of data are not possible to plot on an XY-plane or XYZ-volume, and while there is a potential to create multiple two-variable plots to present all the available data and forecast the presence of many clusters, some information about the probable similarities and relative distances among the points will be lost. Therefore, mathematical data segmentation through estimation of the individuals' or objects' similarities should be performed.

Hair (2010) describes similarity as "the degree of correspondence among objects across all of the characteristics used in the analysis". For each member of a cluster to be possible to compare to any other member, the similarity of each pair of the objects should be estimated.

3.4.3.1 Similarity measures

There are three main ways to measure inter-object similarity: distance measure, correlation measure and association measure. The distance measure is the most commonly applied method in clustering; it calculates the dissimilarity of objects with bigger values representing smaller similarities. The most common distance measure is Euclidean distance, while among the other distance measures there are Manhattan distance, Minkowski method, Chebyshev distance, Mahalanobis distance, Canberra, and log-likelihood distance. Each one of them has the niche of its implementation with its advantages and disadvantages.

Another method to quantify the similarity between a pair of objects is to estimate their correlation and association. While the term association has a very similar meaning to the term correlation, correlation usually implies a linear relationship between variables and the association has a wider meaning of any type of relationship. When the association is measured, the results are scaled to be between 0 and 1 or sometimes between -1 and 1. Zero indicates no relationship between the variables, 1 indicates that the variables have a perfect positive and -1 perfect negative relationship. Association measures are mainly used for non-metric data such as nominal or ordinal measurements. The correlation coefficient is used to analyse the patterns in variable changes across the measurements, not the magnitude of measured variables of the specific member or the mean value of all the observations, which makes it impossible to differentiate the sizes of the objects. For this reason, similarity estimation with correlational measures is rarely used in cluster analysis, as for cluster creation the magnitudes of the objects are often important.

When the decision on similarity measuring technique has been made, a clustering algorithm has to be chosen. All the clustering methods can be divided into two groups based on their algorithm: hierarchical clustering and non-hierarchical clustering (also known as K-means).

3.4.3.2 Hierarchical

The hierarchical method can further be divided into the agglomerative procedure (bottom-up approach) and the divisive method (top-down approach). The main principle behind all hierarchical agglomerative algorithms is to find the most similar points of data and assign them into one cluster, then find other similar points and assign them into another cluster and so on. If one of the points of these closely located pairs is already in a preformed cluster, then the second point becomes attached to the existing cluster. When all the steps are completed, a single cluster possessing all the points should be formed and a dendrogram presenting these cluster merging steps can be made. The dendrogram shows the developed clusters in relation to the distance between the points and the connections between points made by the analysis. Unlike in K-means methods, the data is not classified into any particular number of clusters at the beginning of the analysis. One of the drawbacks of these methods is that if a point has been assigned to a cluster, it cannot be redirected to another, even a more appropriate one.

Divisive algorithms perform the opposite to agglomerative task. It starts with all the individuals or objects in the same cluster, which is divided into two clusters with the most dissimilar points. The action of segmentation is repeated until all the clusters are single-member clusters. These methods are stated to be computationally demanding as they often require running all possible cluster divisions. Depending on the properties that should be accounted for during the segmentation of points, division methods can be monothetic and polythetic. In the monothetic division method cluster members possess a commonly known property that is used as the objective of division. Usually, data classified with this method consists of binary variables which makes this analysis relatively simple and computationally efficient. In polythetic divisive methods, cluster individuals or objects have several similar non-predefined properties, therefore the revision of all variables should be done simultaneously. The main problem of it is considering all the possible splits, and this problem was addressed in Macnaughton-Smith et al. (1964) and Kaufman and Rousseeuw (2005).

Depending on how similarity is measured, or in other words, what distance is calculated, all hierarchical algorithms can be classified into five groups: single linkage (also known as the nearest neighbour), complete linkage (can be referred to as diameter method), geometric centroid, average linkage and Ward’s method. The nearest neighbour method defines the similarity between objects and clusters as the minimum distance between two closely located points. The drawback of this method is that it creates chains connecting two clusters that might not possess a high similarity. Complete linkage method measures similarity as the distance between the two most dissimilar objects in each of the two clusters. During each step clusters with the smallest dissimilarity are combined to form a new cluster. In the geometric centroid method, the similarity is measured as the distance between clusters centroids (average value of the members in a cluster). As a new cluster is created or an existing cluster is modified, a new centroid is calculated. The similarity between clusters measured in the average linkage method is the average distance from all members of one cluster to the members of the other cluster. This approach creates clusters with small variances. Finally, Ward's method calculates the distance by summing the squares between all the points in two clusters for each variable. This method is usually implemented when roughly equally-sized clusters are required.

3.4.3.3 Non-hierarchical (K-means)

Non-hierarchical clustering methods, unlike the clustering ones, do not produce a dendrogram of the data segmentation process. The main idea behind K-means algorithms is not to show the correlation between points and similarity hierarchy but to divide the data into a known number of clusters. These clustering algorithms assign random points to be the centroids of the clusters with the number of clusters (K) predefined by a human. The distance between each point and the centre of each cluster is measured and the point is allocated to the closest centroid's cluster. When all members have been distributed to the nearest clusters, the centroid is recalculated as the average of the cluster's points and the process is repeated. Since the centroids change their position in the initial iterations of the calculations, an object that was in cluster A in the beginning can be relocated to cluster B during further iterations. When the cluster's centroids no further change their location, clustering is finished.

To determine the most appropriate number of clusters Elbow method is usually used. This method requires performing clustering for a range of values of k and to calculate the sum of squared errors (SSE) for each variation. Then, the line chart of SSE against each K value is plotted and the "elbow" or a "knee of the curve" is the number of clusters to use.

As it was mentioned earlier, the initial cluster centroids (seeds) are often chosen at random and based on the way to select them, all K-means methods can be divided into research specified seeds and sample generated seeds. The research specified seeds are selected based on external data such as prior research or other multivariate analysis data. If there is no additional information and no knowledge regarding the cluster profiles, the seeds can be generated from the sample observations (e.g. systematic selection of two points with maximum distance and a point between them) or predefined algorithm such as selecting the first input of data as the first seed and allocating minimum distance to the second seed.

Additionally, all non-hierarchical clustering algorithms can be divided into three groups based on the members' assignment method. The sequential threshold method selects the first seed and includes all the points within the specified distance from that seed to the cluster. Next, it creates a second seed and includes in the second cluster all the points within the distance excluding points that already have been assigned to the first cluster. After that, the third seed is created and the process proceeds. The main drawback of the sequential threshold method is the inability to redirect a member to a more similar cluster if it has been included in an earlier cluster. The algorithm implemented in the parallel threshold method reviews all the seeds simultaneously and assigns the points within a threshold distance from the seed to the closest cluster. The third method, optimizing procedure, is similar to the first two with the main difference that it allows to relocate the points from one cluster to another.

3.5 Decision-making process for building retrofits

Installation of building retrofit measures influences many aspects of building performance such as energy efficiency, environmental and economic sustainability, thermal, acoustic, and visual comfort. Depending on the goals of the retrofit, different retrofit performing criteria variables can be used. These variables act as attainable objectives that quantify the performance of proposed retrofits. Using the criteria variables, a comparison among various retrofit scenarios can be executed to determine the most suitable solution.

However, a retrofit measure successfully performing in one criterion might be lacking in the other. In addition to that, some of the criteria variables can be contradicting each other, creating a dilemma in optimal retrofit selection. Thus, decision-making models are developed to achieve a balance among the objectives to establish the best performing retrofit. Based on the literature review, the development of a decision-making model involves the following parts: selection of criteria type and variables (based on the retrofit's objectives), the establishment of a decision-making method, and selecting a method to assess building energy performance.

The selection of the energy performance method depends on the required complexity of the building model and specific retrofit measures (Manni and Nicolini, 2022). For example, natural ventilation retrofits should be done via fluid dynamics equations and computer software supporting its calculation such as ANSYS. To evaluate the daylight, shading, and solar radiation levels, such simulation engines as Radiance would provide the results. Building energy performance simulation software selected for this research is discussed and justified in the next chapter.

Establishing the criteria type and variables used to evaluate the retrofit options should depend on the objectives of the retrofit. Typically, integration of retrofit into the buildings influences one or more of the following aspects of the built environment: economic, environmental, energy, and social.

3.5.1 Economic impact

The economic impact retrofit poses on the built environment can be evaluated considering many variables. How it is assessed depends on the boundary conditions that are considered.

In the past, the majority of building design and retrofit decision-making was primarily considering initial investment cost only (Yang et al., 2020). Nowadays, however, a more holistic approach includes consideration of building running costs, energy-saving brought by retrofit installation, repair, cleaning and maintenance costs, and disposal costs. Such an approach is called Life Cycle Cost analysis and it will be more closely discussed in Section 3.7.

3.5.2 Environmental impact

The environmental benefits of building retrofitting can be evaluated using many variables, the most common one of which is the global warming potential (GWP). Building energy demand decrease caused by retrofit installation reduces the amount of fossil fuels burned to satisfy the occupants' needs. As a result, fewer GHGs are being released into the atmosphere, which in turn affects the planet's climate. Similarly to the economic impact evaluation, the analysis of environmental impact can be expanded to include the energy used to produce insulation materials, new equipment or other retrofit supplies. LCA offers a methodological approach to estimate various environmental impacts a certain process or service (such as building retrofit) has on the planet and its ecosystem. This approach is discussed more closely in Section 3.8.

3.5.3 Energy impact

Some research considers the energy impact that retrofits pose on building performance (Liu et al., 2020b, Ge et al., 2021, Manni and Nicolini, 2022, Shao et al., 2014), while others include energy variables into either economic or environmental impact (Rey, 2004, He et al., 2021b, Mauro et al., 2015). It can be argued, that even today the primary energy sources are fossil fuels, which are limited non-renewable resources, therefore, it is important to conserve them. However, this side of fossil fuels consumption is difficult to predict due to new fields being discovered and even more challenging to quantify. Calculating the more direct influence energy consumption reductions have on the built environment, on the other hand, can be done either through its economic influence as the building running costs reductions or environmental impact as reductions of emissions.

3.5.4 Social impact

Providing a healthier and more comfortable indoor environment is associated with increased satisfaction with living space, increased productivity and mood, and better health (Tanabe et al., 2007, Fisk and Rosenfeld, 1997, Keatinge et al., 1997). Installation of building retrofit measures can improve building thermal, visual, and acoustic environment, indoor air, and increase safety. Additionally, the reduction of annual energy bills affects the financial stability of occupants. All of these impacts building retrofits have can be attributed to the social impact category. Unlike the economic, environmental, and energy impacts, social impacts are much more difficult to estimate since this criterion’s variables often cannot be directly quantified. Moreover, since they portray an individual’s experience and opinion, they can be subjective and biased. Thus, in this research, it is suggested to not include social impact criteria into consideration when comparing retrofits.

3.5.5 Decision-making methods

The decision-making process of determining the most optimal building retrofit scenario is done with consideration of established criterion variables. When only one variable is considered, the method is considered to be single-objective, while establishing two and more criteria variables creates a multi-objective problem. To achieve a balance among conflicting variables, various studies apply different decision-making methods. Table 3.2 reviews seven scientific papers on building retrofit scenarios evaluation. All of these papers present the execution of different decision-making methods. In addition to that, they implement the various number of criterion variables, with some of the papers considering only one criteria type, while others different combinations of two and three criteria types.

Study	Criterion type	Criterion variables	Decision-making method
Liu et al. (2020b)	Economic, Environmental, Energy	LCC, Lifecycle primary energy demand, lifecycle GWP	Multi-objective weighted sum
Ge et al. (2021)	Energy	ΔE	Single-objective ranking
He et al. (2021b)	Economic, Energy (included in the economic variable)	NPV	Single-objective optimisation
Asadi et al. (2012)	Economic, Energy	ΔE, IIC	Weighted Tchebycheff
Kaklauskas et al. (2005)	Economic	IIC, PBP	Multi-objective multi-stage weighted decision tree
Shao et al. (2014)	Economic, Environmental, Energy	IIC, E_{total}, GWP	Pareto front
Rey (2004)	Economic, Environmental, Energy (included in the economic variable), Social	E_h, E_{el}, acidification potential, thermal, acoustic, and visual comfort, IIC, annual energy cost	Weights and thresholds

Table 3.2 Decision-making process in other research

3.6 Life Cycle Cost analysis

According to Yang et al. (2020), LCC is the sum of the costs throughout the whole life cycle of a product, project or service. It allows decision-makers to evaluate the total costs of the products and select the best investment plan. Unlike the traditional mode of costs calculation that focuses primarily on minimizing the initial investment expenses, LCC estimates the overall costs during the entire life of the product. That includes planning, design, equipment and material costs, transportation, labour, installation costs, operation, maintenance, cleaning, repair, and finally recycling and disposal costs. This shifts the priority from short-term initial cost decreases to long-term benefits.

Depending on the complexity of the project or the product, the number of costs that would have to be considered can vary greatly. With big complex projects involving multiple parties, many materials and a lot of equipment, or spanning through long periods some of the costs can be difficult to predict or hard to acquire the data on. Therefore, with every LCC analysis it is essential to specify the assumptions and boundaries of it, or in other words what costs are considered, which are assumed, and which costs are excluded from the research for various reasons. Based on different methods to specify the types of costs in a project, LCC can be classified in many different ways, two main examples are content dependence and time dependence.

Content dependence classification outlines four main categories of costs: investment, utility, operation, and others. Investment costs involve the project costs and resell/scrap value; utility costs are energy consumption costs, water use and treatment costs; operations costs include administrative, repairing, cleaning, replacement and other maintenance costs; and other costs are responsible for discount, revenue and associated income.

Time dependence classification divides the overall project costs into two groups: initial costs and future costs. The initial costs involve all of the costs necessary to bring the project or a product to a usable operational state. Future costs, on the other hand, are the costs starting from the moment the product has been put to use until the disposal. Some of the future costs can be repetitive, such as annual operation costs, administrative, maintenance, etc. Others do not occur on an annual basis, e.g. overhaul, replacement.

The classification of LCC, specification of different types of costs evaluated, and the established boundaries and assumptions during the analysis depend on the exact product or project that is being analysed. The costs that must be included in the calculations or can be omitted as being not significantly influential should be considered based on the evaluated product as well as the other alternatives that this product is being compared to.

In addition to proving the total costs for the whole life cycle of the product, LCC analysis includes the time value of money into the calculations. The prices of products and services continuously change driven by inflation or deflation. Moreover, the same amount of money now and in the future will have different real earning power depending on when the expenditure occurs. LCC allows for incorporating these variations into the final costs calculations, three most common methods to do that are the net present value method, the equivalent annual method, and the final value method.

Alongside the economic benefits discussed above, Yang et al. (2020) outline three other advantages of implementing LCC:

- It follows the strategy of sustainable development
- Providing assistance during the selection process, it helps to make scientifically proven and effective choices
- It assists in allocating resources more efficiently

3.7 LCC in Built Environment and building retrofit

Applying LCC in the Architecture and Construction industry on a new building implies evaluation of the total costs associated with the building's whole life starting at the point of design conception and ending it at the demolishing stage. According to Davis et al. (2005a), LCC 'is a process of evaluating the economic performance of a building over its entire life'. LCC can also be referred to as LCCA, "whole cost accounting", or "total cost of ownership" in some literature, since it calculates the balance between the initial investment costs and the costs of owning, running and maintaining the building.

Considering the design and construction of new buildings, the main assumption implemented in LCC is that several different designs of a building can meet the exact same specifications and achieve the established goals. Evaluating different initial costs of these designs as well as their operation costs, maintenance costs, end of life (demolishing/recycling) costs, and different expected service life can allow to analyse and compare the total cost of each of the design options. Thus, the results of LCC analysis assist in determining the most cost-effective alternative while compromising between initial costs and long-term savings and help evaluate when the design or system will pay back for its initial investment.

In building energy retrofit, LCC's implementation and results can depend on the final target of the retrofit. In cases where building retrofit is initiated to achieve energy reduction goals set up by the government or other parties, LCC can assist in determining the minimum required IIC to reduce the total annual energy demand of the building by the required percentage. When the disposable amount of money is specified, LCC analysis can propose the best retrofit options for obtaining the biggest energy reductions for the established IIC. In addition to that, if the building undergoes a renovation and the energy conservation strategies have not been given consideration, implementing LCC analysis would allow to evaluate the possibility of integrating sustainable practices into the building renovation plan, justify the potential increase in initial costs, and display the financial benefits caused by operational and maintenance costs decreases.

As it was stated before, the exact boundaries of LCC analysis of a project depend on the project itself and how it will be compared to other alternatives. In residential building retrofit, the baseline building is identical for all of the evaluated options, thus, those building elements that remain untouched will be the same. In this case, calculation of the total costs associated with the building's whole life cycle is unnecessary, because these costs will be equal throughout all of the retrofit choices. Therefore, LCC analysis of a building retrofit project consists entirely of the evaluated set of retrofit measures costs: the sum of the purchase, installation, maintenance, and disposal costs of every individual retrofit measure and the total building energy consumption cost during the retrofit set's service life. Since the baseline building implies no intervention and consequently no initial investment costs, the justification of financial benefits of a retrofit would be based entirely on the balance between all the costs directly associated with retrofit measures installation, maintenance, and disposal and the energy demand reduction costs (comparing baseline building and retrofitted one).

According to (Shah, 2012), typically the greatest part of the overall costs of a building during its life cycle comes from the operational phase with the exact percentage being dependent on the building type and design, local climate, and occupants' behaviour. Considering the individual building systems, the situation is similar to the whole building: operational costs are bigger than the procurement costs, sometimes more than 10 times Wu and Clements Croome (2007). Based on that it can be said that it is highly important to acquire correct data on the operational stage of the building for LCC analysis.

However, being able to accurately forecast the exact operational costs of a building might be a difficult task even when knowing the majority of possible variables such as the building design, precise installed equipment and materials used, local climate, local prices, etc. Annual energy consumption costs of a building are dependent on the occupants' behaviour, which was proven to be responsible for up to 30% of energy demand variations (Eguaras-Martínez et al., 2014, Gill et al., 2010). Residential buildings, unlike public buildings that often have centrally controlled heating and cooling either running 24/7 or only during the pre-set hours and scheduled usage patterns, have very non-uniform energy demand schedules varying from one apartment to another. This variability is exacerbated even more for intermittent part-time part-space conditioned locations such as the HSCW climate zone since the variations occur from room to room.

Uncertainties in predicting indoor human behaviour are not the only risks associated with the selection of best retrofit measures packages that can influence the results of LCC analysis. Among others directly associated with the residents are perceived long payback periods, incorrect interaction with the equipment, low satisfaction rates and sometimes even rejection and disposal of installed retrofits. These risks are often caused by low public participation rates and therefore lack of understanding of the installed building services.

Other uncertainties present in LCC analysis concern the building and equipment itself. As was discussed previously, the expenditures occurring during the operational stage of the building include the total cost of the energy consumed by the building during the retrofit package's service life. Within any package, however, there are different individual retrofit measures with varying service lives. In addition to that, with the anticipated gradual change of climate, changes in both residents' interaction with the building services as well as the building services' effectiveness and the failure rate can also change in a span of retrofit's life. As for the disposal/recycling costs, science and technologies are constantly evolving, providing new cheaper alternatives of materials reuse and recycling methods that could alter the total costs of disposal at the final stage of the retrofit life cycle.

In addition to risks and uncertainties arising from the building or occupants, the current and future state of the economy can also influence the results of LCC analysis. The decision making on retrofit measures includes financial limitations, the introduction of new taxation, changes in energy prices, real and nominal discount rates, inflation and deflation and market price of land and buildings. While some of these factors can be accounted for with relative accuracy by experienced professionals, others can be hard to predict. Some studies address some of the individual abovementioned risks and uncertainties in LCC, however, currently, there is a lack of research on including all of the risks.

Nonetheless, in this research LCC is used to assist in the decision-making process selecting the most financially appropriate retrofit measures in cases of their conjoint or individual installation. LCC has the potential to be more welcomed and interested in among the residential building's occupants than among the developers or public building users since residents bear the financial consequences of building energy design and therefore are economically concerned with operational costs reductions. Thus, it can be used to display the financial benefits associated with building energy retrofit. Currently, there is a lack of research on LCC used for residential buildings in particular in intermittent part-time part-space conditioned areas and its impact on the decision making and retrofit measures selection. This research provides a case of such application for method validation.

3.8 Life Cycle Assessment

LCA is a method to evaluate the environmental impact and resource requirements of a product or a process throughout its life cycle including the extraction of raw materials, their transportation, treatment, products manufacturing, their transportation, use, maintenance, and recycling or disposal. Environmental standards BS EN ISO 14044 and BS EN ISO

14040 outline the methodology for LCA that is used worldwide (BS EN ISO, 2006b, BS EN ISO, 2006a). Muralikrishna and Manickam (2017) define LCA as "a technique for assessing the environmental aspects associated with a product over its life cycle". Thus, from the point of view of consideration that this evaluation involves all stages of the process of product creation, LCA resembles LCC. However, while LCC concerns with the economical side of the project, LCA indulges in the environmental questions.

While the LCA method delivers quantitative results that can be used to compare different alternatives or identify opportunities to improve the overall sustainability of the processes, these results can be different depending on the objective of the research and the evaluated environmental parameters. Sustainability and environmental research involve multiple variables responsible for various damage to the environment, humans, and animal species. Therefore, when performing LCA the following steps of the technical framework are followed.

3.8.1 Goal and scope definition

In this phase of LCA the goal, studied product, system boundaries, life cycle phases, functional unit, and assumptions are defined. The process of establishing system boundaries in LCA is similar to that of LCC, meaning it specifies what data on the environmental performance of the system is included, what is assumed, and what is omitted from the calculations. The geographical area necessary for energy source, transportation, waste management, local sustainability standards, and ecological systems sensitivity evaluations is established together with the timeline. Definition of a functional unit is required to provide a reference for inputs and outputs comparison for different evaluated products or services; it can be mass, volume, one piece of the item produced, a dollar spent on production, etc. This step is crucial to eliminate unnecessary data.

3.8.2 Life Cycle Inventory Analysis (LCIA)

The second step of the LCA framework is data collection. Here, the data on all the inputs and outputs such as resources, energy consumption, water waste, discharged contaminants are accumulated within a set scope defined during the first step. The accuracy of the whole LCA depends on the quality and accuracy of data collected during this step.

3.8.3 Impact assessment

Based on the inventory analysis the impact of the evaluated product or service on the environment and human health is assessed. Any production requires materials, energy, and other resources while it also generates various pollutants at all stages of the manufacturing and material extraction process. The environmental impact driven by these actions was classified by the Society of Environmental Toxicology and Chemistry (SETAC) into three groups: resource consumption, impact on ecosystems, and impact on human health. These groups can be further divided into other categories such as acidification, ozone depletion, global warming, smog creation, etc. Some of the inputs and outputs in LCA can be responsible for the same environmental impact (carbon dioxide and methane both cause global warming) while others could cause different types of environmental impact (carbon dioxide causes both global warming and ocean acidification). To align the environmental impact of different pollutants to one common measurement unit reference substances called characteristic factors are used. Thus, for GHGs the characteristic factor is CO_2 meaning the effect on the environment of all other gasses will be expressed in terms of carbon dioxide's effect. In addition to that, the impact of these groups of emissions can be reflected using different units representing various approaches based on chosen numerical method: impact approach specifies the pollutants, while damage based approach outlines the equivalent of killed species or destroyed land.

3.8.4 Interpretation

The final step in this framework is to analyse and interpret the results. At this stage, the variations are compared to each other and the best alternative is determined; or the weak spots of the whole process is determined and valid suggestions on improvement are proposed.

3.9 Conclusion

The main drivers for sustainable development and building retrofits were given in the previous chapter, while this chapter focused on the methods used to estimate the results of building retrofits and quantify them for comparison.

Firstly, existing analytical and statistical methods to collect data on a city's building stock and analyse it were presented and discussed. They included residential building stock energy consumption simulation methods and multivariate building data analysis and segregation methods. Since commonly applied retrofitting measures were reviewed in the previous chapter, this chapter discussed the decision-making process for selecting specific retrofit measures for analysed buildings. The question of important criteria for retrofit selection was raised with examples from the literature on what parameters were used. A deep review of LCC and LCA was given as the two pillars for economic and environmental evaluation framework for proposed retrofits in this thesis.

Overall, using the results of this literature review this chapter helped to establish specific research tasks and methods to fulfil them.

4 Chapter 4. Research methodology

4.1 Introduction

Research is a systematic investigation in a field of knowledge using appropriate methods to establish facts, solve problems or simply to increase the body of knowledge in that particular field (OECD, 2015). The scientific method most commonly involves the following elements: research approach, observations, questions, hypothesis, experiments, analyses, conclusions and replication (Marczyk et al., 2005). The selection of the research approach as well as the data analyses methods depends on the type of research conducted, type of data collected, the research questions and the desired outcomes of the research (Marczyk et al., 2005).

Based on the application of research, it can be split into two types: pure and applied (Creswell and Creswell, 2018). Pure research, sometimes referred to as basic or fundamental research, is an abstract investigation of theories or hypotheses driven by curiosity. It is done without any specific goal purely to expand human knowledge and understanding of certain areas. Applied research uses existing methodologies and knowledge (obtained by pure research) to address a specific problem.

Analysing the research from the point of view of objectives would give four broad types of research: correlational, descriptive, exploratory and explanatory research (Kumar, 2011).

Exploratory research is implemented when little knowledge on a subject exists to explore and ask questions, and to assess the possibility and feasibility of undertaking this study. Descriptive research describes, defines, or provides a detailed account of a situation, phenomenon or problem. Correlational study evolves around discovering and establishing the existence of a relationship between variables and evaluating it. Marczyk et al. (2005) include correlational research into the descriptive term while adding a predictive type of research, which essentially uses the findings of descriptive (correlational) research on a relationship among variables and attempts to predict one variable from the established knowledge on the other. Lastly, explanatory research studies and explains the reasons for an existing relationship among variables since correlation does not mean causation. While in theory, a research study can be attributed to one of these categories, in reality, it usually possesses the attributes of two or more of the aforementioned research types (Kumar, 2011).

In addition to that, based on the types of data and methods used, research can be divided into three broad categories: qualitative, quantitative, and mixed. In Qualitative research, scientists implement open-ended questions with the main objective to describe the characteristics of objects or events without the attempt to quantify their results through measurements or calculations. Data is typically collected from participants with high importance given to individual meanings and complexity of the phenomenon. The report on qualitative research is often flexible or unstructured and the main questions asked in such studies are how and why. Quantitative research, on the other hand, focuses on numerical data and it has open-ended questions. Quantitative research methods include experiments, statistical, and mathematical techniques, while the reports usually have a defined structure. Similarly to the multiple types of objectives being present in one research, it can also include different types of data, meaning a combination of qualitative and quantitative methods or so-called mixed method needs to be applied. This method combines philosophical assumptions and theoretical frameworks bringing a deeper insight into the problem that otherwise could not be fully covered using only qualitative or only quantitative research.

This research's main aim revolves around building retrofits and how they could be applied to a residential building stock economically and sustainably, which makes it 'applied' research by definition. According to Becher and Trowler (2001), the majority of research on the AEC industry is of applied nature and it can involve different research methods. This study is subject to the AEC industry and sustainability considerations, therefore to showcase such a complex phenomenon, mixed methods are required. To not limit the scope or outcomes of this research to just one research type, multiple sources of data, data types, data gathering, and data analysis techniques are used (Onwuegbuzie and Leech, 2005). The specific methodologies and methods implemented in this thesis are discussed below within the requirements of each objective to achieve the outlined tasks.

4.2 Objective 1

The first objective of this research was of an exploratory and familiarising nature. It reviewed the background of the established problem and current methods and capabilities in addressing it.

4.2.1 Literature review

The literature review is performed on the initial stages of the study to review the existing research in the area of interest, to highlight the gaps in the research, and by doing so validate the necessity for this study (Greenfield and Greener, 2016). In addition to that, it establishes the imperative concepts, types of data, methods and techniques of data collection and analysis used in this field of research. In the later stages of the study, it can be used as a technique to collect data already gathered in other research.

This thesis focuses on evaluating building retrofit scenarios in the HSCW climate zone with Ningbo city used as a case study. Therefore, the selection of appropriate literature for this research included keywords like ‘building’, ‘energy’, ‘performance’, ‘simulation’, ‘retrofit’, ‘refurbishment’, ‘renovation’, ‘sustainable’, ‘sustainability’, ‘building stock’, ‘residential’, ‘China’, ‘HSCW’, ‘Ningbo’. As the scope of the research as well as the required methods and techniques to execute it were determined, additional keywords were added to deepen the understanding and knowledge on the subjects that more directly concerned with the delivery of this project. These keywords included ‘typology’, ‘reference building', 'policies', 'standards', 'occupancy', 'behaviour', 'cluster', 'LCC', 'LCA', 'cost-effectiveness', 'decision-making', 'embodied', 'carbon', 'GHG'. Both American and British spelling was used to perform the literature search and for the acronyms, both abbreviated and full versions were used.

The performed literature collection consisted of peer-reviewed articles from international journals and conferences proceedings obtained from journal databases such as ScienceDirect, Emerald, Springer, MDPI, Taylor & Francis. In addition to that, it also included academic books (available online and in the university's library), other researchers' theses, government standards and governmental and institutional reports (both local and international).

Outputs of the literature review are mainly presented in Chapters 2 and 3, with some information added in later chapters where it was necessary.

4.3 Objective 2

This objective's primary task was to develop reference building models that were proposed to be used in the next two objectives for energy simulation and retrofit evaluation purposes. Thus, it focused on residential building stock's data collection and interpretation and representative models creation.

4.3.1 Onsite and online data collection

Based on the executed literature review, no internationally available research has been done on Ningbo residential building stock and its characteristic data. However, this data is imperative for residential buildings classification, accurate building energy consumption estimation and consequent retrofit scenarios evaluation. Therefore, first-hand data on Ningbo residential stock must be collected online and onsite.

The random sampling method (Govaert, 2009) is used to select 18 residential compounds in Ningbo city, after which the data on buildings in these compounds are collected mainly online via reviewing satellite imagery in spatially correct coordinate systems within Geographic Information Systems (GIS) or occasionally onsite. The procedure and outcomes of this method are discussed in more detail in Chapter 5 of this thesis.

4.3.2 Cluster analysis

Clustering is a method to segment the data into groups with high homogeneity within the groups and high heterogeneity between the groups. This method can be used to analyse the collected residential building stock data and segregate it into different groups representing different building forms. These building groups are essential for establishing prototypical reference residential building models that would serve as the base for all the required energy simulation, retrofit packages assessment, policy guidance, etc.

As was discussed in Section 3.4.3, clustering can be done via hierarchical or non-hierarchical (K-means) methods. The newer statistical analysis software such as SPSS deliver a third method referred to as Two-Step clustering which presents a combination of hierarchical and K-means methods. Two-Step clustering provides an automatic estimation of the appropriate number of clusters, it can be used on both categorical and continuous variables and, unlike hierarchical and K-means methods, it can analyse large sets of data, which can be useful while working with a city's building stock (Everitt, 2011). Based on this, it is suggested to implement a Two-Step clustering method for this research.

However, before any clustering is initiated, standardisation must be performed. It might be problematic to evaluate the similarity of objects, if the measured variables have different metrics and scales, therefore, standardizing the data is an important step in multivariate data analysis. Many clustering techniques are sensitive to the difference in scales and magnitudes of the data, resulting in variables with bigger values and larger standard deviations exerting a greater impact on the results. Data standardization allows to easily compare variables that initially were on different scales and had different value magnitudes. Moreover, it eliminates the effects of scale within the variable, making it irrelevant what units were used for the measurement.

The most common technique to standardize data is z-scoring, which can also be referred to as standard scoring or autoscaling. The z scores are calculated for each measurement by subtracting the mean and dividing by the standard deviation of the variable as is presented in Equation 4.1 below:

$$z = \frac{x - \bar{x}}{\sigma} \tag{4.1}$$

where x is the variable, $\bar{x}$ mean of the population and σ the standard deviation.

The resulting values of the variables have a mean of 0 and a standard deviation of 1 with a positive value being above the measured mean and the negative value below the mean, while the magnitude of the value presents how many standard deviations the measurement is away from the mean.

After the standardisation of variables is completed and the clustering technique is chosen, the similarity measure must be selected. Euclidean distance, sometimes referred to as straight-line distance, is the most frequently used measure of distance. It can be found using Equation 4.2 below:

$$d_{ij} = \left[\sum_{k=1}^{p}(x_{ik} - x_{jk})^2\right]^{1/2}$$

(4.2)

where d_{ij} is the dissimilarity between objects *i* and *j*, *k* the variable, x_{ik} and x_{jk} the objects' variable values and *p* the number of dimensions or variables. If plotted in Euclidean space, d_{ij} would be the physical distance between two points.

These outlined techniques and methods are applied to Ningbo's residential building stock for reference building forms classification and establishment. The results of these methods are discussed in Chapter 5. Combining it with the typical thermo-physical characteristics outlined in local and national building energy efficiency standards (Ministry of Construction of PRC, 2001, Ministry of Construction of PRC, 2010, Ministry of Construction of Zhejiang, 2015) studied during the literature review allows for the development of representative electronic models. These models provide the basis for completing the following tasks.

4.4 Objective 3

This objective focused on the creation and validation of building energy models. Due to the lack of publicly available data on residential buildings energy consumption a questionnaire survey method was used to obtain the actual data on EUI of Ningbo city's residential building stock. This method also provided means for the data collection on local heating and cooling behaviours of the residents. The obtained data were analysed, compared to similar existing research and used for energy models creation and validation through building energy consumption simulation.

4.4.1 Questionnaire

According to Greenfield and Greener (2016) surveys are “collecting information about the same variables from a sample of cases”, and a structured questionnaire is the most common method of obtaining the structured set of data. A questionnaire is a written list of questions, the answers to which are recorded by respondents (Kumar, 2011). This method allows for large quantities of data to be collected in a relatively short period.

In some cases the whole studied population can be asked to participate in the questionnaire, in other cases like this research, it is impractical and impossible to attempt the data collection from the whole population. Therefore, the sampling method must be used. The simple random sampling method is one of the most common and simplest to implement. Its aim is to assign equal probability to every population member to be selected for participation. According to (Greenfield and Greener, 2016) there are four main methodologies for administering questionnaires: face-to-face administration, telephone, postal, and internet based (can be further subdivided into email and web pages). Each method of questionnaire distribution has its own advantages and disadvantages. Thus, questionnaires administered by postal mail tend to have poor response rates (Marshall, 2005), internet based surveys tend to generate more data due to wider spread among the population, however, they can be biased towards elderly participants who do not use computers. Face-to-face questionnaires omit this limitation, but they are more time and labour consuming. Similarly, questionnaires distributed via telephone require substantial time investment. Balancing these positives and negatives and addressing aforementioned issue of bias, in this research the survey is executed via two methods: via web page and face-to-face. This ensured the random selection of participants, which in turn meant that each member of a population had an equal chance to be given an opportunity to participate.

Questionnaire designs can be structured, unstructured, or quasi-structured. Structured questionnaires are comprised of close-ended questions; they provide little discrepancies among the respondents, they are easy to follow and quick to answer. While there is less possibility for the participant to elaborate their reply, this type of questionnaire is usually used in quantitative research where large quantity of data would have to be managed. Unstructured questionnaires use open-ended, vague questions with possible discussions. They offer more in-depth answers, but require tedious and time-consuming post-coding. A mixture of open-ended and close-ended questions comprise a quasi-structured questionnaire. Since in this research questionnaire was used for collecting factual (rather than opinion) data from hundreds of participants, it consisted of mostly close-ended questions.

One of the main challenges of questionnaires is the fact that the respondents read pre-written questions and reply to them themselves with no possibility to verify their understanding. Since there is no one to clarify the exact meaning of questions, the questions must be simple and easy to understand to ensure the correct data collection. Assuming the same respondent is being interviewed, ‘a reliable question is one to which respondents give the same response on different occasions’ (Greenfield and Greener, 2016). Questionnaire pre-tests are suggested to be done for two primary reasons: to check respondents’ understanding of the questions and (where applicable) to collect data on common answers to unstructured questions for the purpose of simplifying them into structured multiple-choice ones. To guarantee that the questionnaire executed in this research meets the reliability requirement, an initial run of the questionnaire was performed. After that, the comments and replies given by the respondents were taken into account to improve the questionnaire, and the final survey was performed.

The exact questionnaire layout as well as its results and discussion are presented in Chapter 6.

4.4.2 Selection of building energy simulation software

Nowadays, a wide range of building performance simulation tools is available internationally to architects, engineers, designers, researchers, and other experts. Some of them focus on one specific aspect of building performance (e.g. DIALux specialises with artificial and natural lighting), others (IES-VE, Ecotect, etc.) evaluate the building as a whole with all of its systems included in the calculations. These tools can also vary based on the design development stage they can be used for (conceptual, schematic, development), and consequently based on the types of users these tools were made for (architects, designers, engineers). Thus, to select the most suited to this research's needs building performance simulation software, it is important to evaluate the advantages, disadvantages and limitations of different available options.

Since this research studies a whole building energy performance and implements different retrofit measures focusing on various building systems, it is crucial to select one tool that would be capable of accounting for all possible interventions. Table 4.1 lists six common building performance simulation tools all of which can be used to evaluate building retrofit scenarios. These tools were further assessed regarding their accessibility (if the university has the license to use it), BIM (Building Information Modelling) compatibility, directed users (engineer users required) and the directed stages of design (later stages of design preferable).

BIM compatibility was considered to be important in this study for the selection of both building modelling and energy simulation tools because BIM is already a mandate for all centrally procured public construction projects in the United Kingdom for the benefits it provides to the AEC industry, and due to the government incentive, private companies are also extensively adopting BIM (HM Government, 2012). An increasing amount of new buildings to be constructed worldwide are modelled with BIM. AEC companies in China also explore the advantages of implementing BIM in their construction projects (Bernstein et al., 2015). The fact that different parties can work on the same project simultaneously using a common platform allows for an efficient, faster and cheaper information sharing process. Incorporating BIM data-rich models into energy simulation provides higher level of detail and accuracy.

The selection of directed users being engineers and later stages of building design were required to ensure the selected tool would be able to accommodate for changes in building services systems, which are usually designed by engineers at the later stages of design. Based on these specifications it can be seen that two building simulation tools from Table 4.1 meet the requirements: Ecotect and IES-VE. However, starting from March 20, 2015, Autodesk discontinued the support and development of Ecotect, making it impractical to use this tool for future research. This leaves IES-VE as the best option for this research.

	Accessible	BIM	Users	Conceptual	Schematic	Development
Green Building Studio	×	✓	A/D	▬	▬	
Design Builder	×	×	A/E	▬	▬	
Ecotect	✓	✓	A/D/E	▬	▬	▬
eQUEST	×	×	A/E	▬	▬	▬
IES-VE	✓	✓	A/D/E	▬	▬	▬
EnergyPlus	✓	×	A/E		▬	▬

Table 4.1 Six most common building energy simulation tools with their advantages and disadvantages

IES-VE is a set of integrated analysis applications capable of dynamic annual building energy simulations with daily and hourly time steps. These applications cover building envelope creation, solar, lighting, micro- and marco-flow analysis, HVAC system design, whole-building energy simulation, and more. IES-VE uses both the CIBSE (Chartered Institution of Building Services Engineers) Admittance method and ASHRAE's Hear Balance method in its calculations. The internal gains are presented on an hourly basis with both sensible and latent heat supplied from people, lights, equipment and other heat sources. More detailed variables such as thermal mass, thermal bridging, buoyancy, wind pressure coefficients, and air flow through cracks are also accounted for in this software.

In addition to that, building energy simulation results provided by this software are in good agreement with the actual experimental results. Oleiwi et al. (2019) evaluated the accuracy of IES-VE software simulation in a hot tropical climate. They compared the results provided by the software with the ones collected on-site in a Malaysian double-storey house and the simulated data were found to be valid and reasonably accurate. As for the colder climates, Ben and Steemers (2014) used IES-VE to evaluate the energy performance of UK heritage housing; the simulated results were observed to be very close to the actual energy usage data. Based on all the aforementioned advantages of the IES-VE software package, it is decided to use it for building energy consumption simulation, building models (created in Revit and imported in IES-VE as gbXML files) verification, and retrofit scenarios simulation and evaluation.

4.4.3 Energy analysis

Energy flow in a building consists of different types of inputs and outputs. Building energy simulation software allows calculating building energy supply demand that is required to sustain specified indoor conditions in the building and to run required equipment. IES-VE software specifies five main building energy demand groups namely heating, cooling, lighting, equipment, and domestic hot water which combined constitute the total building energy demand (Equation 4.3):

$$E_{total} = E_c + E_h + E_l + E_{eq} + E_{DHW} \tag{4.3}$$

where E_{total} is the overall annual energy demand of the building during one year of service, E_c is the annual cooling energy demand, E_h is the annual heating energy demand, E_l is the annual lighting energy demand, E_{eq} is the annual equipment energy demand, and E_{DHW} is the annual domestic hot water energy demand.

The main goal of building energy retrofit is to reduce the total annual building energy demand by decreasing one or multiple building energy demand groups. The energy performance of the retrofit depends on the magnitude of the energy reduction ΔE which can be calculated by comparing the total energy demand of the studied building before and after the retrofit. The baseline building energy consumption E^b shows the energy performance of the existing building without interventions with existing active and passive systems. Integration of energy-efficient retrofit measures into the building decreases building energy demand with the new retrofitted building energy consumption being E^r. Thus, ΔE can be found using the following equation:

$$\Delta E = E^b - E^r \tag{4.4}$$

where E^b is the total annual energy demand of the baseline building (before retrofit) and E^r is the total energy demand of that building after the retrofit.

4.5 Objective 4

The last objective constituted the application of building retrofit scenarios for their evaluation purposes on models developed in previous objectives according to the proposed Economic and Environmental assessment framework. The most economically and environmentally beneficial combinations of retrofit measures were outlined and the results of the framework were established.

4.5.1 Cost-effectiveness analysis

As it was discussed in the previous chapter, LCC ‘is a process of evaluating the economic performance of a building over its entire life’ (Davis et al., 2005b). It accounts for all the expenses associated with the building starting at its design stage and ending at the demolishing stage. Thus, the calculations of the life cycle cost of the building should involve the cost of all of the objects, materials and equipment in the building, their associated delivery, installation, maintenance costs, etc. However, the LCC can also be used to compare the life cycle cost of different sets of retrofit measures and compare them to the baseline or ‘business as usual’ scenario with no retrofit. In that case, the focus of cost calculations should be directed from the whole building to the specific analysed set of retrofit measures. For that, the following equation adapted from O’Neill et al. (2021) can be used:

$$LCC = IIC + PV_u + PV_t + PV_d \tag{4.5}$$

where IIC is the initial investment cost of the chosen set of retrofit measures (materials, equipment, labour and installation costs included), PV_u is the present value of the building during the usage phase with the chosen set of retrofit measures implemented, PV_t is the present value of transport costs associated with the purchase, delivery and installation of the chosen set of retrofit measures, PV_d is the present value of the disposal costs (reuse, recycling or demolishing) of the selected set of retrofit measures.

In Equation 4.3 PV_u is a cumulative term used to address the total costs associated with the usage phase of the retrofit, including the annual energy consumption costs of the building (electricity, gas, and other sources of energy), maintenance, cleaning, and repairing costs of the retrofit equipment, and any taxation costs related to the property ownership. It should be noted that if taxes have to be paid for during any other stage of the building lifecycle (e.g. disposal phase), these costs would have to be added to that term of the equation. Some research also includes another term to this equation representing the financial benefits of reselling the building (Arja et al., 2009, Fregonara and Ferrando, 2018), in this research, however, it is assumed that such action does not take place, therefore, this term is not included. In addition to that, due to the lack of sufficient data and for simplification reasons, the cost calculations for transportation, disposal, property taxes, cleaning, repairing and other maintaining costs, as well as the potential government incentives and subsides for sustainable construction are not included in this research. Based on this, the final LCC equation used in this research is as follows:

$$LCC = IIC + NPV_E \tag{4.6}$$

where NPV_E is the net present value of building energy demand cost during the expected service life of the building with the integrated retrofit, and it can be found by Equation 4.7:

$$NPV_E = \sum_{t=1}^{n} \frac{C_{E(t)}}{(1+i)^t}$$

(4.7)

where n is the service life of the analysed set of retrofit measures, $C_{E(t)}$ is the annual energy consumption cost in the year t, and i is the discount rate. Assuming that with the installation of retrofit measures the total annual energy demand of the building E_{total} would stay constant throughout the expected service life of the retrofit, $C_{E(t)}$ can be calculated using the following equation:

$$C_{E(t)} = E_{total} * \rho * (1+k)^t$$

(4.8)

where ρ is the current price of energy, k is the annual rate of the energy price increase. Assuming that the annual discount rate and the annual rate of energy price increase are both equal to 1% for simplification reasons, NPV_E can be found by the following equation:

$$NPV_E = E_{total} * \rho * n$$

(4.9)

Based on that, the previous LCC equation (Equation 4.6) can be transformed into Equation 4.10 below:

$$LCC = IIC + E_{total} * \rho * n \tag{4.10}$$

Thus, considering that in many cases higher retrofit integration levels yield greater building energy demand reductions, the life cycle cost of a set of building retrofit measures represents a balance between the initial investment cost and the total building energy consumption cost during the retrofit service life. The smaller LCC is, the more financially beneficial the analysed set of retrofit measures is.

The main disadvantage of implementing LCC analysis for a retrofit cost evaluation is the requirement to use *n* (service life of the analysed set of retrofit measures) in the calculations. Different retrofit measures have different expected service lives, therefore, using an average number might not be enough to determine if a particular retrofit measure presents a good financial investment. Implementing this average number into the calculations will overestimate the building energy cost decreases of short-term retrofits during these *n* years and underestimate the energy cost decreases of long-term retrofits. Thus, this assumption might lead to a situation where retrofit measures with small expected service lives are being preferred over more long-lasting options because the cost of energy decreases caused by these long-lasting measures will not be able to repay for IIC in the specified average *n* years. To address this problem, this research uses a payback period (PBP) which can be found by the following equation to validate the cost-effectiveness of every individual retrofit measure by comparing its PBP to its service life.

$$PBP = \frac{IIC}{\Delta E * \rho} \tag{4.11}$$

4.5.2 Environmental impact analysis

To compare the environmental impact of different building retrofit measures and retrofit packages, LCA is used. The data for this study is acquired via a rigorous literature search. This study performed cradle to gate analysis, meaning all the data before the product is at the manufacturing facility's gates ready to be transported on site is included. This approach was selected for two reasons: firstly, the data on the use phase is studied in this research and is collected through building energy simulation, while the data on the end-life of the equipment is scarce with little to no literature available on the topic; secondly, the end-life is difficult to predict due to potential newly invented recycling methods. When selecting the functional unit for the overall retrofit life cycle assessment the whole building is used since the comparison is made among different retrofit alternatives for the same building form. As for the specific individual retrofit measures, the functional units are the same as in the literature.

One of the most commonly discussed environmental impacts of any manufacturing processes and products is the release of GHG that cause global warming. Since different gasses cause a different degree of influence on the climate, it is a worldwide practice to express the impact of all greenhouse gasses in terms of the GWP that CO_2 has. Thus, in this study, the GWP of the retrofit is used as the main indicator for LCA. Following the established LCA boundaries, to determine the environmental influence of a building retrofit package the GWP of individual retrofit measures generated during their production is contraposed the decreased GWP driven by reduced building energy consumption (Equation 4.12).

$$\Delta GWP^{r} = \sum_{i=1}^{N} GWP^{r} - GWP^{r}_{\Delta E} \tag{4.12}$$

where ΔGWP^{r} is the difference in global warming potential of a building with the retrofit package being installed (comparing to the baseline building), GWP^{r} is the global warming potential of each individual retrofit measure calculated from cradle to gate, N is the total number of individual retrofit measures in the retrofit package, and $GWP^{r}{}_{\Delta E}$ is the global warming potential of the building energy demand difference caused by implemented retrofit. Based on this formula, the proposed retrofit is beneficial for the environment when ΔGWP^{r} is negative, meaning the decrease in the building's GWP.

It was decided to not include any other groups of environmental impact since they are rarely covered in the literature. In addition to that, various building retrofit measures are responsible for different emissions released during their production, which makes the process of obtaining these data and normalising it for analysis and comparison reasons challenging research beyond the scope of this thesis.

4.5.3 Weighted sum method

This building retrofit scenarios evaluation research studies several objective functions developed by energy analysis, LCC and LCA, values of which are different for each individual retrofit measure. These functions include IIC, ΔE, E_{total}, PBP, NPV_E, ΔGWP^r, GWP^r, $GWP^r_{\Delta E}$, LCC. Comparing two or more retrofit measures taking into account all of these objective functions would require a multi-objective optimisation method. The weighted sum method is widely used to convert multi-objective problems into single-objective ones, after which this new function can be directly and easily used to compare alternative solutions.

Careful consideration of each of the multi-objective functions' roles in the weighted sum method shows that inclusion of each one of them is not necessary because some of these functions are used to calculate the other functions and some of them reflect the results of others. For example, IIC is used to calculate both LCC and PBP, however, on its own, it is an independent function that will have different values for each of the retrofits. It is very important to include it into the pool of criteria (weighted functions) since it is one of the most influential points in any retrofit. If the proposed retrofit is too expensive and the client cannot afford it, the retrofit will not be initiated and none of the other parameters can influence this decision. Another two intertwined parameters influencing other functions are E_{total} and ΔE. When comparing retrofit alternatives these two parameters affect PBP, NPV_E, $GWP^r_{\Delta E}$, ΔGWP^r and LCC. ΔE is used as the primal function to evaluate the energy performance of the proposed retrofit action. In addition to that, it can reflect the annual financial savings resulting from the decreased building energy demand. The addition of this function to the criteria would balance the influence of IIC on the results of the weighted sum method since IIC is desired to be minimised and annual financial savings to be maximised, however greater initial investments usually yield greater energy reductions. The first year's annual financial savings can be found using the following equation:

$$S_{\Delta E} = \Delta E * \rho \tag{4.13}$$

The environmental side of the retrofit decision process in this research is presented by three objective functions: ΔGWP^r, GWP^r, and $GWP^r_{\Delta E}$. GWP^r is an independent function similar to IIC, $GWP^r_{\Delta E}$ is fully dependent on the annual building energy consumption reductions caused by the retrofit installation, while ΔGWP^r is calculated using the previous two functions. Thus, the inclusion of ΔGWP^r into the pool of criteria would account for the results of all three functions. The proposed three criteria namely IIC, $S_{\Delta E}$, and ΔGWP^r

directly or indirectly reflect the results of all of the developed objective functions and thus are assumed to be enough to perform the weighted sum analysis of economic and environmental benefits of building retrofit scenarios.

The next decision that the weighted sum method requires to be done is the selection of weights to be assigned to each criterion. The results of the weighted sum method strongly depend on the selected weighted criteria and chosen weight coefficients. The sum of all of the assigned weights is equal to one (Equation 4.14) and they represent the relative importance of each of the evaluated criteria.

$$\sum_{i=1}^{m} w_i = 1 \tag{4.14}$$

where *m* is the total number of evaluated criteria (in this research 3) and *w* is the assigned weight.

According to the literature review discussed in Chapter 2, in China, the general public is more concerned with the improvement of their life and financial savings related to energy reduction costs, than environmental protection. Local governments, on the other hand, focus on achieving the targets on the number of houses that energy retrofits are performed on with little concern about the actual performance of the retrofit. Based on this, it can be said that the financial criteria have a greater influence on the decision-making process during a building retrofit initiation, and therefore, they should be assigned greater weights than the environmental criterion. Assuming that the relative importance of IIC and $S_{\Delta E}$ are equal since if the retrofit's IIC is too high the retrofit will not be performed and if $S_{\Delta E}$ is not big enough the retrofit decision will not be made either, the final proposed weights for IIC, $S_{\Delta E}$, and ΔGWP^r are 0.4, 0.4 and 0.2 respectively.

4.5.4 Economic and Environment (EE) Score assessment framework

While determining the most rational and appropriate building retrofit scenario it is essential to account for the influence of individual retrofit measures on each other's building energy reduction results. To do that, it is required to perform a simulation of different retrofit measures combinations. This research suggests evaluating the possible intervention into 12 passive and active building systems (external wall, windows, heating/cooling system, PV panels, etc.). Assuming that the decision is to be made between performing a retrofit on that system and not performing it, the final number of all retrofit measures combinations would be $2^{12}=4096$. This research, however, attempts to assess different variations that could be proposed to be installed for each system. Including all of these variations (discussed more closely in Chapter 7) would raise the total number of all possible retrofit measures combinations to 68,871,264. This number of different simulations would require impractically high computational and time investment. To minimise the total number of analysed retrofit measures combinations, it is suggested to reject all the economically or environmentally impractical variations (based on energy analysis, PBP, LCC, and LCA) at the initial stages of building retrofit evaluation. To do that, the efficiency and applicability of separate individual retrofit measures should be evaluated comparing them to the baseline building with no retrofit intervention. After that, the combinatorial energy simulations can be performed with a further rejection of impractical alternatives. The proposed framework consists of 6 steps outlined and discussed more in-depth below:

Step 1. LCC, PBP and LCA of all of the individual retrofit measures. Initially, computational energy simulation of each of the proposed variations of 12 passive and active building systems is performed on every building typology. These energy simulation results obtained using IES-VE building simulation software are used further to perform the cost-effectiveness analysis (LCC and PBP) and LCA of the evaluated retrofit measures.

Step 2. Rejection of potentially inefficient and inappropriate retrofit measures. The cost-effectiveness analysis (LCC and PBP) and LCA performed in the previous step can potentially show that some of the analysed retrofit measures during their service life do not reduce enough energy demand to cover the IIC or to decrease the GWP of the building. These results primarily depend on two variables: IIC or GWP^r and the annual energy reductions ΔE associated with the installation of that retrofit measure. The main objective of all of the retrofit measures in the ‘Energy Reduction’ group is to reduce the overall building energy consumption. Thus, if a retrofit measure was proven to be financially or environmentally ineffective in the case of its individual installation on a baseline (non-retrofitted) building, it will not be effective in a more energy-efficient retrofitted building either. Based on this, all of these potentially inefficient and inappropriate retrofit measures can be rejected at this stage of the analysis to decrease the number of further combinations of retrofits and the required simulations.

Step 3. The normalisation of the retrofit measures' comparative criteria. The economic and environmental criteria discussed in Sections 4.5.1 and 4.5.2 and obtained data in the previous steps can be used to compare two individual retrofit measures. Direct comparison, however, is problematic, since these criteria have different magnitudes and metrics, thus, they need to be normalised. These criteria can be divided into two groups: beneficial criteria and non-beneficial criteria. The beneficial criteria are those that are desired to have maximum values, they are $S_{\Delta E}$ and ΔGWP^{r}. Non-beneficial criteria are the ones in which the minimum values are thought to be the best alternatives; in this research it is IIC. The following equations are used to normalise them:

$$x_{cr} = \frac{X_{cr}}{X_{c\,max}} \tag{4.15}$$

$$x_{cr} = \frac{X_{c\,min}}{X_{cr}} \tag{4.16}$$

where Equation 4.15 is used for beneficial criteria, Equation 4.16 is used for non-beneficial criteria, X_{cr} is the observed value of c criterion of r retrofit measure, $X_{c\,max}$ is the maximum value of *c* criterion observed among all of the evaluated retrofit measures, $X_{c\,min}$ is the minimum value of *c* criterion observed among all of the evaluated retrofit measures, and x_{cr} is the normalized dimensionless value of *c* criterion of *r* retrofit measure. Since the values of comparative criteria are compared within themselves to the maximum or minimum value (depending on if the criterion is beneficial or not), the normalized value of the best alternative would always be equal to 1 and all the other alternatives would have positive values less than 1.

Step 4. Addition of weights to the normalized dimensionless values of criteria. The weighted sum method is one of the widely used approaches of selecting the best alternative based on multiple criteria. Thus, it is used in this research to transform a multi-objective decision problem of retrofit measures selection to a single objective problem using the following formula:

$$d_{cr} = w_c * x_{cr} \tag{4.17}$$

where w_c is the assigned weight of criterion c, and d_{cr} is the dimensionless weighted value of c criterion of r retrofit measure.

Step 5. Calculation of EE Score and ranking. Based on the selected environmental and economic criteria that are used to evaluate building retrofit measures and the assigned weights reflecting the importance of each criterion, the final EE Score of each individual retrofit measure can be calculated as a sum of dimensionless weighted values (Equation 4.18).

$$EE\ Score_r = \sum_{i=1}^{m} d_{cr} \tag{4.18}$$

The higher the EE Score, the better the attainment of economic and environmental goals is with the integration of that specific retrofit measure into the building. Using this approach, all of the analysed individual building retrofit measures can be ranked depending on their EE Score from the best (which is suggested to be implemented first) to the worst ones.

Step 6. Integration of the best individual retrofit measure into the building and using it as the baseline. To evaluate the results of combinatorial retrofit measures installations, the energy consumption simulation can be done for step-by-step integration of individual retrofit measures following their ranks. Thus, the individual retrofit measure that was ranked first based on EE Score in the previous step is installed into the building as the most beneficial one. This retrofitted model is used as a new baseline building for cost-effectiveness and life cycle analyses of all the other retrofit measures that were ranked lower following the directions given in Step 1 and continuing with the other steps. This approach creates a continuous loop of building retrofit measures analysis, prioritising the most advantageous retrofit measures while rejecting those, that could not perform satisfactorily in case of combinatorial installation.

4.6 Conclusion

This chapter reviewed the established scientific methods and overall methodology used to execute this research. The chapter was structured to address each objective outlined in Chapter 1 of this thesis. It implements a combination of qualitative, quantitative, and mixed methods depending on the specific objective and task. Qualitative research was mainly conducted on retrieving and reviewing information from the literature. Quantitative research methods were applied to give concise, measurable, and comparable characteristics to the data while implementing statistical methods. Mixed methods were used when the descriptive nature of tasks required to employ both quantitative and qualitative research providing a deeper insight into the subject. Table 4.2 shows the application of research paradigms reviewed in Section 4.1 on each objective.

	Research paradigm
Objective 1	
Literature review	Qualitative
Objective 2	
Building form data collection	Mixed
Cluster analysis	Quantitative
Objective 3	
Questionnaire	Mixed
Simulation software selection	Qualitative
Energy analysis	Quantitative
Objective 4	
Cost-effectiveness analysis	Quantitative
Environmental impact analysis	Quantitative
Weighted sum method	Quantitative
EE assessment framework	Mixed

Table 4.2 Philosophical research paradigms applied to each objective.

5 Chapter 5. Building form survey and models creation

5.1 Introduction

To ensure sustainable development in cities, it is necessary to design and construct energy-efficient buildings and improve the energy efficiency of existing building stock through retrofitting. Doing so requires extensive analysis of the existing building stock, its physical and thermal characteristics, and the influence of different building parameters on the final energy consumption in the building. In addition to that, it would also require careful consideration and evaluation of various methods and techniques to improve both the indoor environment and building energy efficiency.

Development of residential building typologies provides an economically and time-efficient approach to accurately represent the existing residential building stock on city-scale for energy simulation, optimal retrofit scenarios investigation, indoor environment evaluation and further required studies. However, it also requires sufficient building characteristics data, which is not always accessible. According to the literature review discussed in Chapter 3, there is a lack of international research on building typologies creation for HSCW climate zone, especially for Ningbo city.

This chapter describes methods used to collect and analyse building stock data in low data availability scenarios and applies them to Ningbo city's residential building stock to fill the existing gap in research. The first section describes statistical methods used to gather a representative sample of buildings used for further research. The second section reviews multivariate data analysis implemented to critically evaluate the collected sample and segregate it into manageable groups of buildings. The third section studies the governmental regulations that the current and previously constructed buildings need to follow to determine the minimum building envelope thermal characteristics these buildings possess. Finally, the collected and analysed results are used to develop reference building form models representable for each building type. These models are verified in Chapter 6 via energy simulation and actual energy consumption comparison and are used further in Chapter 7 for building retrofit measures evaluation.

5.2 Building sampling and data collection

Ningbo city Zhejiang province in China was chosen to implement the developed residential building typology creation methodology. One of the main reasons behind that decision was a unique combination of local climatic conditions, municipal services, and building standards, which will be discussed further in detail. Another important reason was the author's proximity to the location, which ensured more straightforward access to the necessary data than any other city in China. Ningbo is a port city with a population of 8.542 million (China Statistics Press, 2020) located in southeast China below the Yangtze River Delta and near Shanghai (Figure 5.1). It consists of six urban districts, two county-level cities and two prefectures. The central part of the municipality is comprised of three districts: Yinzhou, Haishu and Jiangbei.

Figure 5.1 Location of Ningbo city on the map of mainland China

According to MoHURD (2015)**,** China can be divided into five climate zones which are 'Sever Cold', 'Cold', 'Hot Summer Cold Winter', 'Hot Summer Warm Winter' and 'Mild'. Ningbo belongs to the HSCW zone with the average hottest month's temperature being around 30°C and 5°C average coldest month temperature line crossing it (Ministry of Construction of Zhejiang, 2015). The HDD(18°C) (Heating Degree Day) is equal to 1374.8°C*d and CDD(26°C) (Cooling Degree Day) is 319.4°C*d; on average the summers in Ningbo are hotter than in other geographical locations with the same latitude in the world, while the winters are 8-10°C colder (Yu et al., 2009b). The perception of weather by inhabitants is also influenced by very high humidity levels varying around 80% throughout the year and by winds with average speed being between 11 km/h and 14 km/h with wind gusts reaching 50 km/h. The city is exposed to moderate amounts of rainfall of 1500 ml/year annually majority of which happens during the summer monsoon season (NATIONAL BUREAU OF STATISTICS, 2021). With these cold winter temperatures and possible light snowfalls, the buildings must shelter users from the hot summer temperatures of the subtropical climate and the cold humid conditions during winter. However, because Zhejiang province belongs to the south part of China, according to the requirements of the national heating policy (MoHURD, 1993), central heating is not typically provided in the area leading to uncomfortable indoor winter temperatures (Hu et al., 2016). In addition to that, the local building design standards are not as strict as in the North part of China, resulting in poor building energy performance.

Due to the difficulty of obtaining and analysing the data for all residential buildings in a multi-million city like Ningbo, in this research, a smaller and more manageable sample of buildings will be chosen for analysis. Simple random sampling is the most basic type of probability sampling, where ‘each unit in the population has an equal probability of inclusion in the sample’ (Bryman and Cramer, 2004). If the studied population is known or desired to be divided into regions or strata from which simple random sampling takes place, it is known as stratified random sampling (Thompson, 2012). The construction period was determined to be one of the main building characteristics that predetermine the building’s energy performance since it describes the minimum requirements for building envelope and windows heat transfer coefficients, airtightness and potentially building shapes. It is also one of the most accessible data on a city scale. Thus, the stratified random sampling method was used to select building samples from each construction period in the same ratio as it is present in the actual building stock.

From 1990 until 2019, a total of 147.5 million m^2 of new residential buildings floor space was constructed in Ningbo (Figure 5.2). 18.2% was constructed before 2002, 34.1% between 2002 and 2010, 25.7% between 2011 and 2015 and 22% after 2015 (China Statistics Press, 2020). Many of those buildings belong to residential communities – often gated blocks of different building types, each comprising a neighbourhood built in the same year, operated and maintained by the same management company (Cheshmehzangi and Butters, 2017, Bray, 2006). According to the Ningbo government, there are 2440 residential communities in Yinzhou, Haishu and Jiangbei combined (Ningbo Municipal Government Office, 2019) and approximately 328503 residential buildings in the six urban areas districts combined (Shang et al., 2021).

The residential communities analysed in this research presented in Figure 5.3 and Table 5.1 cover different construction periods, various building types and all the studied city districts.

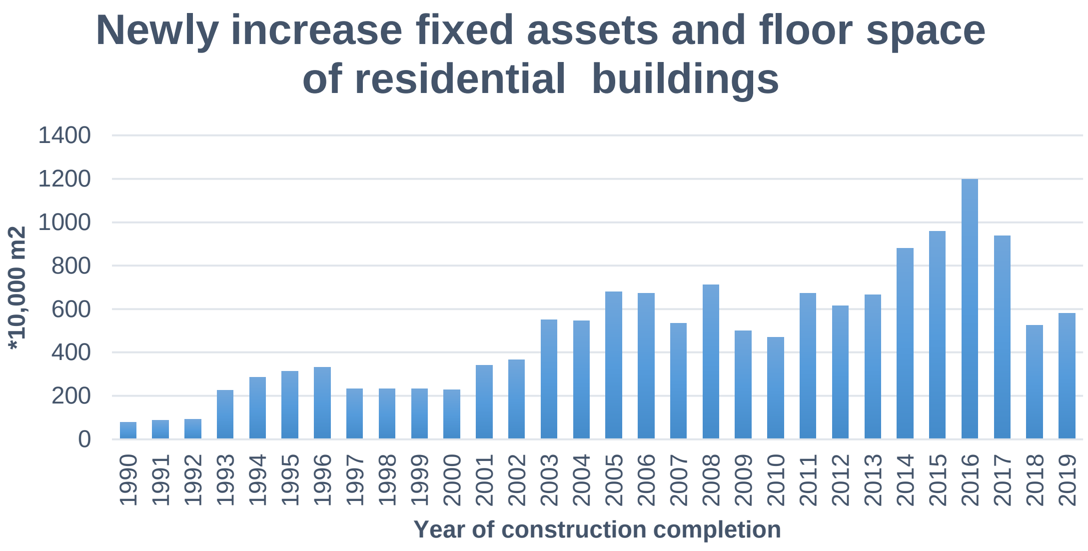


Figure 5.2 Newly constructed residential buildings floor space during the period from 1990 till 2019

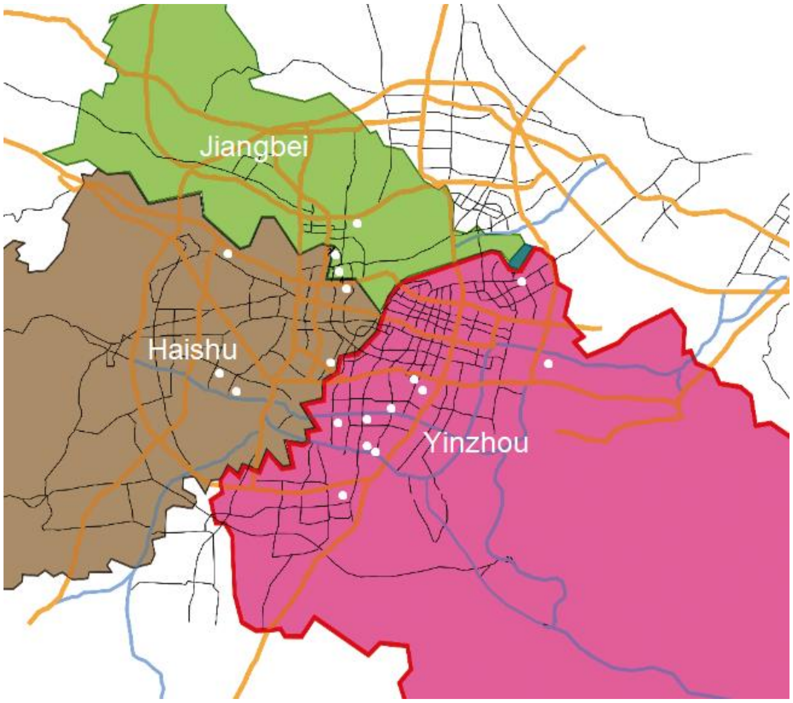


Figure 5.3 Location of analysed residential communities on Ningbo city’s map (generated with Google)

Residential community	District	Construction Year	Building types
宁波东海富别墅 Ningbo Donghaifu Villa	Yinzhou	2014	3 floors, 24 floors, 27 floors, 30 floors, 31 floors
华泰剑桥一期 Huatai Cambridge Phase I	Yinzhou	2002	6 floors
中海雍城世家 Zhonghai Yongcheng Family	Yinzhou	2009	3 floors, 17 floors
金桥水岸花园 Jinqiao Waterfront Garden	Yinzhou	2006	17 floors, 23 floors, 27 floors, 28 floors
宁波格兰郡庭小区 Ningbo Grand County Court Community	Yinzhou	2016	5 floors, 6 floors, 7 floors, 15 floors, 18 floors, 25 floors
高塘花园 Gaotang Garden	Haishu	1997	7 floors, 8 floors
南裕小区 Nanyu Community	Yinzhou	1996	6 floors
宁波锦江年华 Ningbo Jinjiang Years	Jiangbei	2003	7 floors
宁波江北北区繁景花园西 Jiangbei North District West Fanjing Garden	Jiangbei	1998	2 floors, 3 floors
峰锦丽庭 Fengjing Liting	Haishu	2016	11 floors, 18 floors, 22 floors
葑盛昉 Feng Shengfang	Haishu	2015	6 floors
宁波天沁家园 Ningbo Tianqin Home	Jiangbei	2006	10 floors, 11 floors, 15 floors, 17 floors, 18 floors
宁波荣安府 Ningbo Rongan Mansion	Yinzhou	2013	18 floors, 35 floors, 36 floors
都市嘉园 City Garden	Yinzhou	2014	7 floors, 10 floors, 11 floors
悦澜湾雅苑 Yuelan Bay Garden	Yinzhou	2015	3 floors, 18 floors
江山万里 Country Wanli	Yinzhou	2016	4 floors, 25 floors, 27 floors, 29 floors
御江山花苑 Imperial Country Garden	Yinzhou	2019	7 floors, 11 floors, 16 floors, 17 floors
北宸府 North Chen Houses	Haishu	2020	18 floors, 22 floors, 26 floors, 30 floors, 33 floors

Table 5.1 Additional information on analysed residential communities

To determine the sample size representative of the city residential building stock, the following formula proposed by Krejcie and Morgan (1970) was used:

$$s = \frac{X^2NP(1-P)}{d^2(N-1)+X^2P(1-P)}$$

(5.1)

where s is the required sample size, X^2 is the value of chi-square for 1 degree of freedom at the desired confidence level (equals to 3.8416 for 0.05 confidence level), N is the population size (total amount of buildings), P is population proportion (assumed to be 0.5 as suggested for maximum sample size), and d is the degree of accuracy (chosen to be 0.05). According to this calculation, for the sample to represent 328503 buildings, the sample should contain at least 383.7 buildings.

Thus, publicly available resources such as search engines (Google, Baidu, etc.) and the orthorectified satellite imagery viewed in GIS were used to retrieve the vital data on 385 residential buildings from the residential communities discussed above. The construction period proportions of the chosen sample were maintained close to the ones present in the actual residential building stock: 70 buildings constructed before 2002 (18.2% of the total number), 131 buildings between years 2002 and 2010 (34%), 100 buildings between years 2011 and 2015 (26%) and 84 buildings after 2015 (21.8%). Using the building footprints, the perimeter and the area of one floor were calculated. To determine the number of floors and the size of the windows, panoramic views of streets provided by Google maps and Baidu Maps were used. These data allowed the calculation of the WWR and C_f.

During this data collection process, it was observed that several buildings in the same communities had identical physical characteristics such as building size, shape, window sizes, etc. It was decided to include only one example of the identical buildings into the analysis to prevent the introduction of identical points into the analysis. However, if the building possessed any difference from other similar buildings, i.e. a glazed or unglazed balcony or a different size window, both variations were included. Moreover, there were no buildings constructed pre-2002 taller than 10 floors in the analysed samples. As the National Bureau of Statistics (2000) states, in the year 2000 in Zhejiang province, only 2.5% of buildings were 7 floors and taller, supporting the lack of high-rise buildings constructed before 2002 in the analysed sample.

It was also observed that initial designs and constructed buildings had open balconies. However, many residents preferred to glaze their balconies following construction, which directly influenced the actual WWR and might cause inconsistencies between planned energy consumption and actual consumption. This proves the necessity of collecting data as constructed and updating this data based on the actual residents' actions, preferences, and needs.

5.3 Cluster analysis

Cluster analysis was used to segregate the collected data into several manageable groups from which representative buildings could be created. The initial iterations of clustering implemented four parameters (Number of floors, C_f, WWR and Floor area) as suggested from the literature review in Chapter 3 converted using the Z-score standardisation method. The ANOVA table, including the F test (Table 5.2) showed a lower significance of WWR compared to the other three variables while generating the clusters. Therefore, it was decided to exclude it from the cluster determining variables.

ANOVA

	Cluster		Error		F	Sig.
	Mean Square	df	Mean Square	df		
Zscore(Floor)	41.162	5	0.095	222	431.229	0.000
Zscore(Area)	41.994	5	0.077	222	547.436	0.000
Zscore(Cf)	37.982	5	0.167	222	227.335	0.000
Zscore(WWR)	20.448	5	0.562	222	36.385	0.000

Table 5.2 ANOVA table with F test of the created clusters with the inclusion of WWR into determining variables

Two-step auto-clustering analysis with Euclidean distance measure (as discussed in Section 4.3.2) and Akaike’s Information clustering Criterion (AIC) was adopted to determine the optimal number of clusters. AIC is introduced into two-step clustering to balance the increase of likelihood by introducing a penalty to each parameter to eliminate the possibility of creating a model where each point is its own cluster (Naik et al., 2007). AIC was selected over BIC (Bayes Information Criterion) for its simpler formula (Bozdogan and Sclove, 1983). Table 5.3 shows the AIC results for a different number of clusters created. As a rule of thumb, smaller values of AIC indicate a better solution. The ratio of Distance Measures can also be evaluated to support the most optimal selection with the greater value indicating a “better fit”. From Table 5.3 it can be seen that 6 clusters is the optimal number of clusters as it provides the smallest AIC 114.706 while still possessing a relatively large Ratio of Distance Measures of 2.380 compared to other solutions.

Each of the six created clusters has at least one characteristic distinguishably different from all the other clusters (Figure 5.4). Thus, clusters 1 and 2 have the same average number of floors, similar floor area with cluster 2 buildings being bigger, and different shape coefficients. Cluster 3 buildings are taller and have a greater average area than clusters 1 and 2, and cluster 4 buildings are larger than cluster 3 buildings. The average number of floors and C_f of clusters 5 and 6 are very similar, however, the average floor area of cluster 5 is almost half that of cluster 6, justifying the segregation of these clusters.

Auto-Clustering

Number of Clusters	Akaike's Information Criterion (AIC)	AIC Change	Ratio of AIC Changes	Ratio of Distance Measures
1	484.611			
2	238.538	-246.073	1.000	2.629
3	152.385	-86.153	0.350	2.169
4	119.138	-33.247	0.135	2.988
5	115.996	-3.142	0.013	1.139
6	114.706	-1.290	0.005	2.380
7	121.122	6.415	-0.026	1.396
8	129.120	7.998	-0.033	1.117
9	137.537	8.417	-0.034	1.035
10	146.075	8.539	-0.035	1.333
11	155.478	9.403	-0.038	1.100
12	165.117	9.638	-0.039	1.066
13	174.902	9.785	-0.040	1.093
14	184.875	9.974	-0.041	1.416
15	195.444	10.569	-0.043	1.068

Table 5.3 Results of Auto-clustering using three determining variables

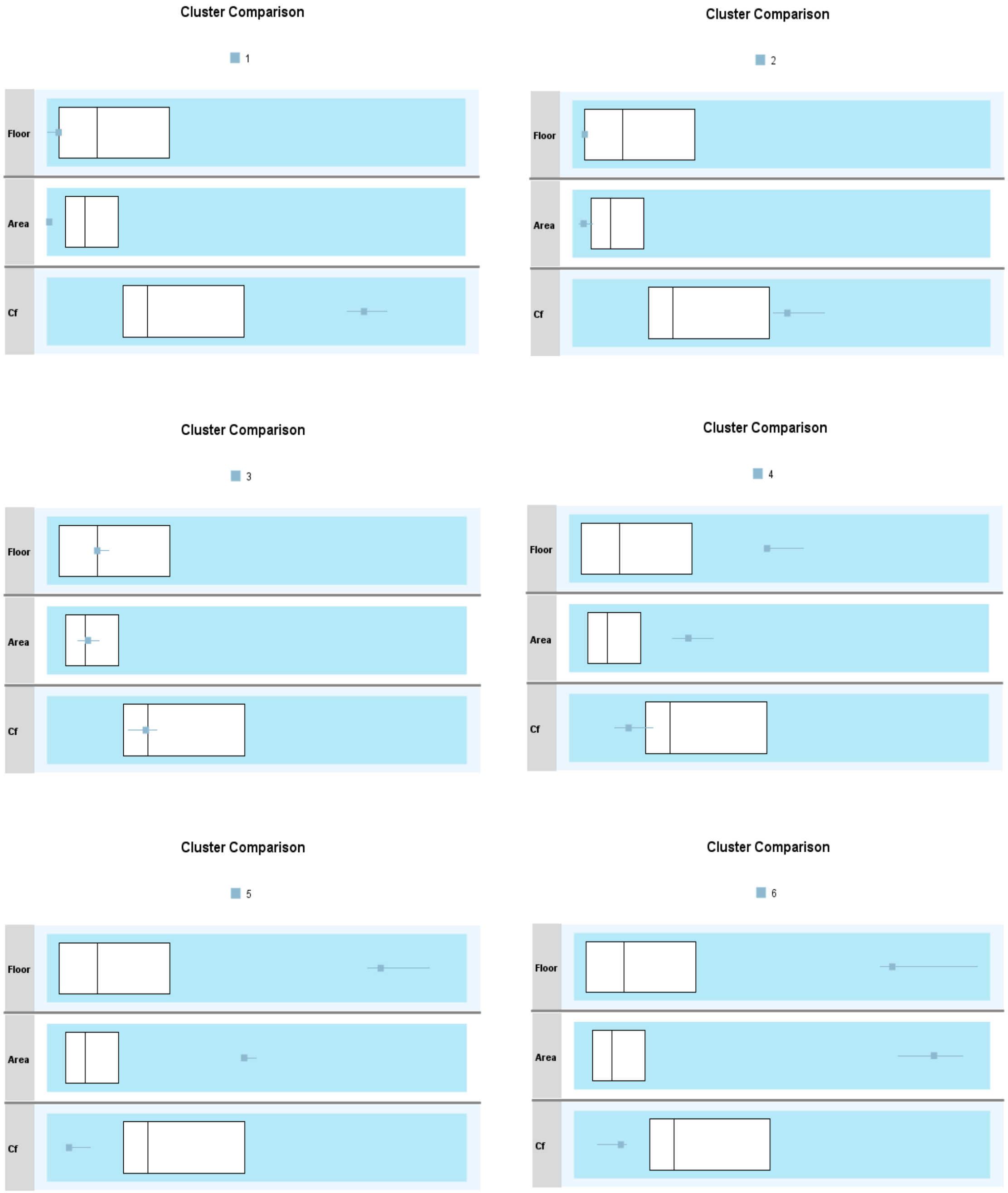


Figure 5.4 Comparison of the created clusters' variables on a bar chart

The Code for design of civil buildings (Ministry of Construction of PRC, 2005) outlines four types of buildings based on their height, which are low-rise for buildings with 1-3 floors, multi-storey for 4-6 floors, middle-rise for 7-9 floors and the high-rise for buildings higher than 28m or 10 floors. Building samples collected in this research contained a variety of buildings beyond these limits, and the clusters themselves represented different building types that could not be attributed appropriately following the groups suggested by the standard. Therefore, the created clusters were named as follows: Villa, Terraced House, Low-Rise (LR), Middle-Rise (MR), High-Rise Tower (HRT) and High-Rise Panel (HRP) (Table 5.4). Villa cluster contains all the single-family buildings, Terraced cluster contains buildings accommodating two or more families, where one family usually occupies rooms on different floors of the building. LR cluster combines all the buildings with 4 and up to 12 floors, while MR cluster comprises buildings with 13-24 floors. Both of the High-Rise (HR) clusters have buildings with 25 floors and more with HRT buildings possessing an area smaller than 20,000 m^2 and HRP buildings being greater. The only exception in the clusters is a building with 18 floors and 25612 m^2 area, which was placed by the algorithm in the HRP category for its big floor area. For the creation of representative buildings, however, it was treated as an MR building.

Cluster	Building type	Number of floors	Area, m^2	C_f	WWR
1	Villa	2.6	317	0.759	0.240
2	Terraced	3	1146	0.586	0.234
3	Low-Rise	6.9	3086	0.382	0.233
4	Middle-Rise	18.9	9207	0.328	0.231
5	High-Rise Tower	30.5	13803	0.272	0.288
6	High-Rise Panel	30.2	25625	0.282	0.352

Table 5.4 Characteristics of created clusters

5.4 Building envelope design

There are two types of residential building design standards: national for specific climate zone and local; the newly constructed buildings should meet specifications described by both of these standards. Table 5.5 outlines building envelope parameters provided by the first design standard for energy efficiency of residential buildings in HSCW zone JGJ134-2001 (Ministry of Construction of PRC, 2001). The table in the standard provides different specifications for heat transmission coefficient based on a different index of the thermal inertia of materials. However, since that specification is unknown, the worst-case scenario is taken as the minimum requirement to be met. Additionally, there are different specifications based on the average coldest month temperature. This research assumed that the coldest month temperature is below or equal to 5°C for the whole city since the 5°C line crosses Ningbo.

JGJ134-2001		
Window U, W/m^{2}K	WWR≤0.25	4.7
	0.25<WWR≤0.3	3.2
	0.3<WWR≤0.35	3.2
	WWR>0.35	2.5
Roof U, W/m^{2}K		1
Wall U, W/m^{2}K		1.5
Floor U, W/m^{2}K		1.5
Door U, W/m^{2}K		3
Internal Wall / Floor U, W/m^{2}K		2
Air permeability (crack flow coefficient), m^3/m*h	1-6 floors	3.5
	7+ floors	3

Table 5.5 Building envelope parameters specified in JGJ134-2001

In 2003 the Ministry of Construction of Zhejiang province issued the first local standard for energy efficiency of residential buildings (Ministry of Construction of Zhejiang, 2003). Still, this research will not cover it because it lists the same specifications for the building envelope as JGJ134-2001 issued earlier. The newly developed national JGJ134-2010 (Ministry of Construction of PRC, 2010) and local DB33/1015-2015 (Ministry of Construction of Zhejiang, 2015) standards reviewed in Table 5.6 divided the buildings based on their heights specifying different parameters for low-rise, middle-rise and high-rise buildings (following the standard limits described above). In addition to that, DB33/1015-2015 also had different specifications for north and south walls, more options for an index of the thermal inertia of the materials, and if the windows have or do not have shading devices. Similarly to the previous table, Table 5.6 presents the worst heat transmission coefficient taken from the standards as the minimum requirement that had to be met. Additionally, for the selection of window heat transmission coefficient, it was assumed that all of the studied buildings did not have any shading on the windows.

		JGJ134-2010		**DB33/1015-2015**		
		≤3 floors	≥4 floors	≤3 floors	4-9 floors	≥10 floors
Window U, W/m^{2}K	WWR≤0.2	4	4.7	2.2	2.4	2.4
	0.2<WWR≤0.3	3.2	4	2.1	2.2	2.4
	0.3<WWR≤0.4	2.8	3.2	2	2.1	2.2
	0.4<WWR≤0.45	2.5	2.8	1.9	2	2.1
	WWR>0.45	2.3	2.5	-	-	-
Roof U, W/m^{2}K		0.6	1	0.7	0.7	0.8
Wall U, W/m^{2}K		1	1.5	1.5	1.5	1.8
Floor U, W/m^{2}K		1	1.5	1	1	1.5
Door U, W/m^{2}K		2	2	2	2	2
Intern. Wall / Floor		2	2	2	2	2
Air permeability (crack flow coefficient), m3/m*h		1-6 floors	7+ floors	1-6 floors		7+ floors
		2.5	1.5	2.5		1.5

Table 5.6 building envelope parameters specified in JGJ134-2010 and DB33/1015-2015

As it can be seen in the table, even though the inclusion of all of these criteria provided greater variability and flexibility to the standard, sometimes (based on the assumptions in this research) it resulted in 2015's standard requiring worse heat transmission coefficient of building envelope elements than 2010s. Thus, for the creation of typologies, it was decided to use the older standard requirement in cases where the resulting requirement from the newer standard was lower than that of the older standard. Finally, based on these standards, assumptions, collected and analysed building data, and providing one year for building construction and the standard enforcement time frame, the building envelope elements requirements used in this research are as shown in Table 5.7:

	Year of Construction	Heat transfer coefficient, W/m^{2}K						Air permeability, m^3/m*h
		Roof	Wall o	Floor	Door	Wall i	Window	
Villa	Before 2002	1.5	1.7	2	4.5	3	4.7	
	2002-2010	1	1.5	1.5	3	2	4.7	3.5
	2011-2015	0.6	1	1	2	2	3.2	2.5
	After 2016	0.6	1	1	2	2	2.1	2.5
Terraced	Before 2002	1.5	1.7	2	4.5	3	4.7	
	2002-2010	1	1.5	1.5	3	2	4.7	3.5
	2011-2015	0.6	1	1	2	2	3.2	2.5
	After 2016	0.6	1	1	2	2	2.1	2.5
LR	Before 2002	1.5	1.7	2	4.5	3	4.7	
	2002-2010	1	1.5	1.5	3	2	4.7	3
	2011-2015	1	1.5	1.5	2	2	4	1.5
	After 2016	0.8	1.5	1.5	2	2	2.2	1.5
MR	2002-2010	1	1.5	1.5	3	2	4.7	3
	2011-2015	1	1.5	1.5	2	2	4	1.5
	After 2016	0.8	1.5	1.5	2	2	2.4	1.5
HRT	2002-2010	1	1.5	1.5	3	2	3.2	3
	2011-2015	1	1.5	1.5	2	2	3.2 (4)	1.5
	After 2016	0.8	1.5	1.5	2	2	2.4	1.5
HRP	2002-2010	1	1.5	1.5	3	2	2.5	3
	2011-2015	1	1.5	1.5	2	2	2.5 (3.2)	1.5
	After 2016	0.8	1.5	1.5	2	2	2.2	1.5

Table 5.7 Overall building envelope characteristics of each building form for every analysed construction period

5.5 Building form models creation

The Revit building design software was chosen to create the reference buildings due to its high compatibility with IES-VE simulation software that will be used further in Chapter 6. Another reason for selecting Revit for models creation is that it is capable of delivering highly detailed data-driven parametric BIM models.

The developed BIM models can be used in future studies some suggestions of which are given in Chapter 8.

Buildings constructed in the same period tend to possess similar characteristics, thermal properties, and construction materials, driven by the market and the established standards. Even though, that the actual construction materials may vary from one building to another, especially among different construction periods or different types of buildings, all facilities were created to have the same structural and thermal materials for simplification in this research. Figure 5.5 displays the materials used for the creation of all building types constructed before 2002. These constructions were made using pre-existing Revit materials. Floor construction materials include ‘cast-in-place concrete’, ‘concrete slab topping’, and ‘rigid foam insulation board’. The roof consisted of ‘cast-in-place concrete’, ‘concrete slab topping’, ‘rigid foam insulation board’, and ‘bituminous roofing material’. The wall comprised of ‘common brick’ on the outside, ‘loose fill insulation’, ‘concrete masonry units’, and ‘gypsum wall board’ as the inside finishing material. For the rest of the construction periods, the materials used were the same, with slight variations of insulation material thickness to reach the required heat transfer coefficients.

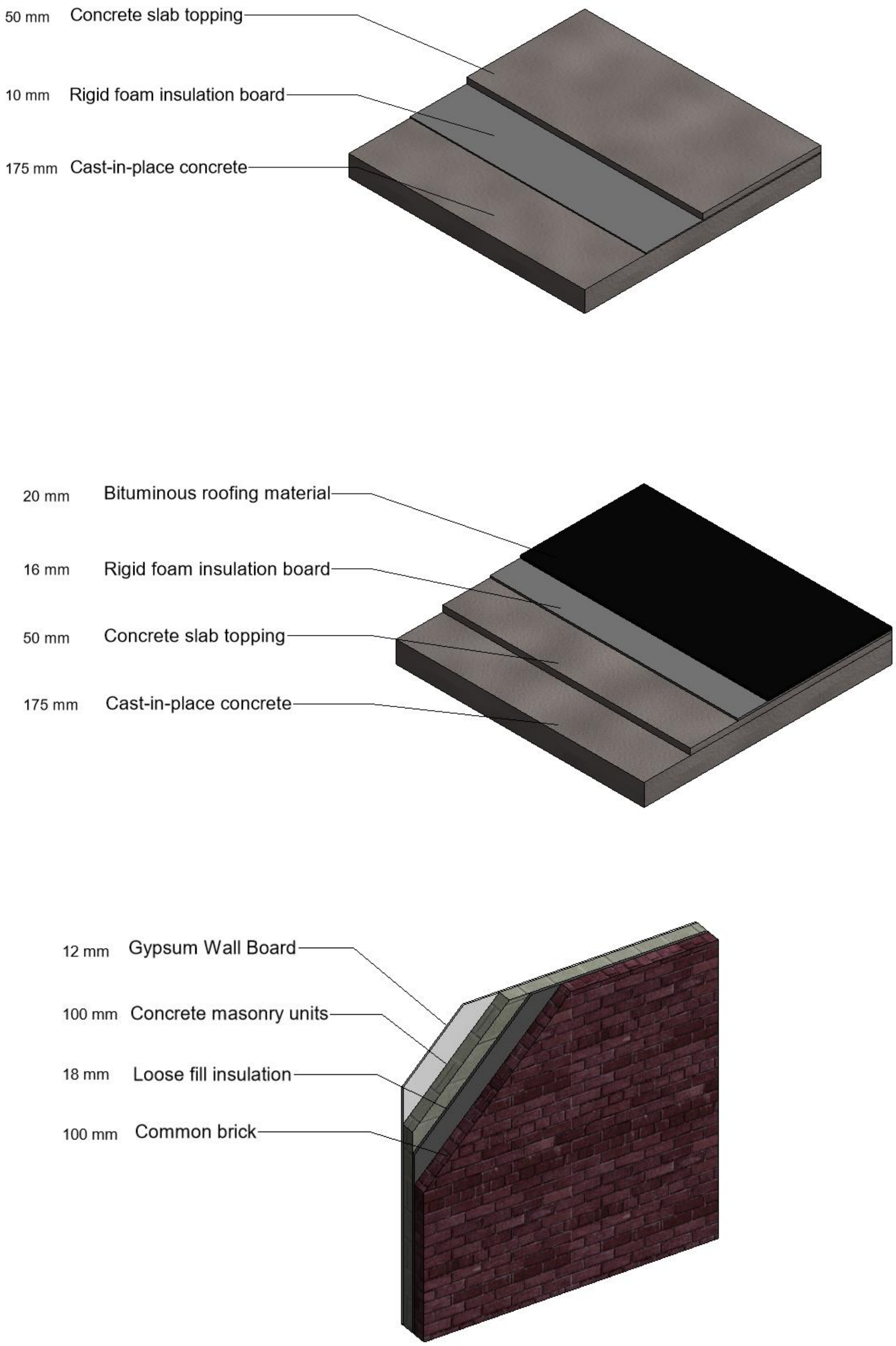


Figure 5.5 The breakdown of construction materials used in the developed building models

Windows' and doors' thermal properties are not as easily modified as the walls' in Revit, however, the software provides a variety of analytic construction options from which the closest to the desired window heat transfer coefficient can be chosen. While additional options can be input into the code of the software, these changes do not transfer to IES-VE for the simulation easily. Therefore windows and doors were selected from the premade options as is shown in Table 5.8:

	Heat transfer coefficient, W/m^{2}K	Analytic construction in Revit
Window	4.7	1/8 in single panes with 1/4 in cavity
	4	Double glazing - domestic
	3.2	Double glazing - domestic
	2.5	Small double-glazed windows - low-E coating
	2.4	Small double-glazed windows - low-E coating
	2.2	Low-E double glazing - domestic
	2.1	Low-E double glazing (1/4 in + 1/4 in)
Door	4.5	Metal
	3	Solid core wood
	2	Door - wood - hollow core - wood storm

Table 5.8 Windows and Doors Revit analytic construction used in the developed building models

Figure 5.6 presents examples of reference building form models created in Revit based on the associated building characteristics derived from the clusters. The latest two standards JGJ134-2010 and DB33/1015-2015 provide suggestions on the maximum WWR for different façades of the buildings, specifying that the south façade of every building should have the highest WWR and the east and west sides have the lowest ratio as is usually applied to all buildings in the northern hemisphere of the planet. These specifications were met during the creation of the building models. Villa, Terraced, and LR building form models each have four reference buildings (with exactly the same form) with different analytic constructions and heat transfer coefficients based on the different construction periods. MR, HRT, and HRP have three reference buildings each. 21 reference building form models were created as is shown in Figure 5.7.

Figure 5.6 Reference building form models created in Revit

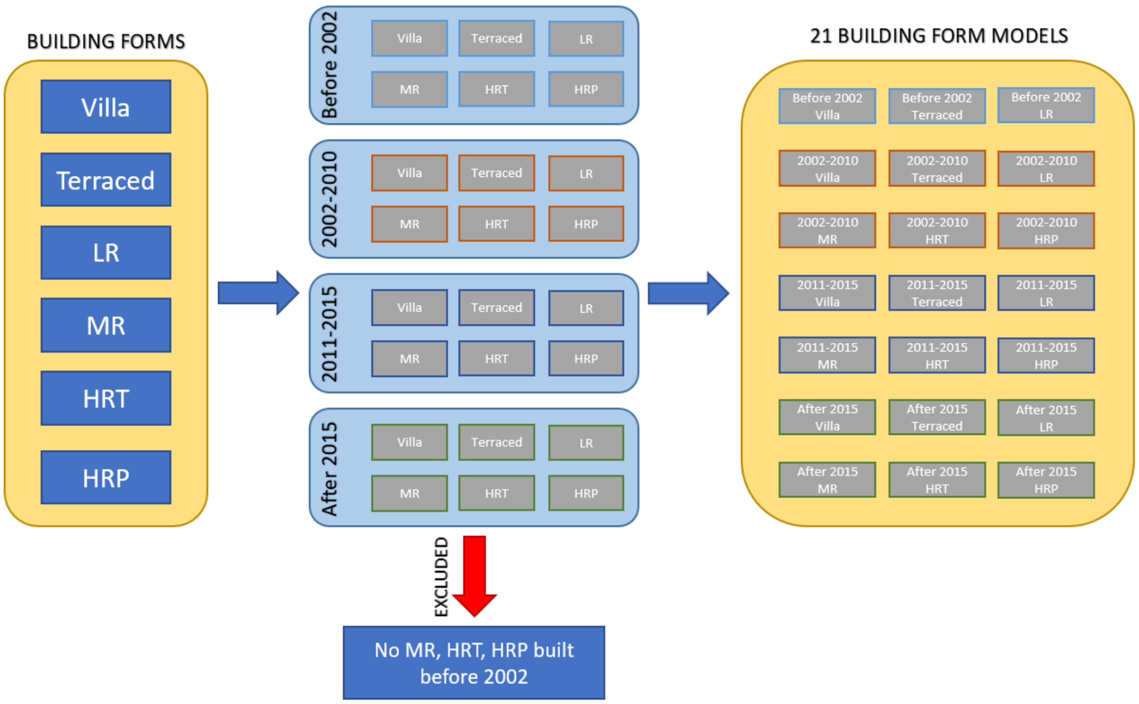


Figure 5.7 Flow chart of reference building form models creation

5.6 Conclusion

Achieving higher energy efficiency in buildings requires gathering a vast amount of data on building stock and understanding different relationships among various building characteristics. This chapter focuses on the first part of this requirement that is the building form survey. Thus, this chapter implements stratified random sampling with construction period as the main stratifying characteristic to collect the real existing residential building stock data from 18 residential building communities. To analyse these data, a two-step cluster analysis is implemented to classify the buildings into 6 building form groups based on their shape coefficient, floor area and the number of floors. In addition to that, empirical data from local and national building design standards were used to develop the required representative building form models with building envelope characteristics close to the existing ones.

The created building form groups are all different and represent the variability of the actual residential building stock in Ningbo as is. Implementation of Revit as the design software ensures a high possibility to easily modify the reference buildings if creating an actual single building is needed or if more actual data is available for higher precision evaluation. Overall, 21 developed reference building form models provide the flexibility of scaling the research down to a community or street study or scaling it up to a city level. In addition to that, the developed models also provide the flexibility of purpose as they can be used for energy consumption simulation, indoor environment evaluation, facilities management, various visualisation purposes, urban management and decision making.

6 Chapter 6. Building energy models creation and building typologies verification

6.1 Introduction

Energy consumption in residential buildings depends not only on the building's characteristics but also on the actions that the occupants choose to take or not to take. The number of people occupying the same space is important for energy consumption estimation since each person acts as a passive heat generator. Nonetheless, treating them as passive residents in the simulations would yield inaccurate results. Occupants' interaction with the living space, their personal preferences for indoor temperatures, heating and cooling regimes and other factors can contribute to up to 30% of the variance in energy consumption (Gill et al., 2010, Eguaras-Martínez et al., 2014).

The range of people's thermal comfort characteristics (temperature, humidity, airspeed) to be considered comfortable, and their thermal adaptation actions vary. They depend on many factors such as age, gender complexion, previous thermal experiences, income, culture, etc. (Kim et al., 2013, Schweiker et al., 2018, Albuainain et al., 2021, Fanger, 1970, Fanger and Toftum, 2002, Frontczak and Wargocki, 2011) Thus, to simulate energy demand in residential buildings accurately, occupant behaviour profiles used for the simulation need to be specifically designed to represent the actual heating and cooling schedules present in local residential buildings. However, the literature review showed a gap in the research regarding the heating and cooling preferences in Ningbo city, thus, this Chapter resolves this problem by collecting and analysing first-hand data on heating and cooling in Ningbo city’s residential buildings.

Another point of interest while creating digital building energy models is verifying them by comparing them to the real energy consumption data. Currently, there is no publicly available data on the energy demand of Ningbo city’s residential building stock detailed enough to be used for developed typologies verifications or building retrofit scenarios evaluations. Therefore, these data must be collected in this research.

To address the two issues specified above, a questionnaire survey is performed to collect data on the actual building EUIs and heating and cooling behaviours in Ningbo city. The results of this questionnaire (reviewed, analysed, and discussed in the first half of this chapter) are used to develop building energy models representative of local heating and cooling behaviour. The energy demand of created building typologies (produced based on building form models from Chapter 5 and building energy models from Chapter 6) is compared to the reported energy consumption for verification purposes.

6.2 Data collection and analysis: Questionnaire survey

6.2.1 Content of the questionnaire

Resident heating and cooling behaviour and residential energy consumption data collection was conducted in two steps: the initial and final questionnaires. The initial questionnaire was designed to focus on the energy consumption data and had a primary goal of understanding if the participants had any difficulties in answering the questions. The study was conducted according to the Economic and Social Research Council (2012) Framework for Research Ethics guidelines and approved by the Institutional Research Ethics Panel of the University of Nottingham Ningbo China. Hard copies of the questionnaire were distributed to willing participants in three of the studied residential communities. During the data collection process, many participants gave comments regarding the difficulty and inconvenience of specifying their electricity or gas bills for different months of the year. Further clarification of their comments revealed that it would be simpler to answer it based on an average monthly bill in a season. Thus, the final questionnaire with 16 questions was developed in English and Chinese based on the amended initial one. It aimed to collect data on the residents' buildings and apartments general information, energy consumption, and occupant behaviour.

The questionnaire can be found in Appendix A and it consisted of 4 sections:

- The first section had four questions inquiring about general background information on the residents, their living spaces, and the residential communities. This information was used to determine the year of construction of the participant's building (as the participants often could not report on the year of construction of the building they lived in, but had an option to write it down if they knew) via an online search engine Baidu. The year of construction was needed to attribute the response to one of the building types created in the previous chapter.

- The second section included 3 questions on participants' average electricity and gas consumption. These questions aimed to collect data on overall energy consumption in different building typologies to verify the energy consumption simulation results.

- The third section comprises 4 questions on occupants cooling behaviour. The questions were created to gather data on how, when, and how often occupants use cooling systems in their buildings. The answers to these questions are essential for the creation of representative occupant schedules in the building energy simulation software. The energy consumption in buildings depends on the residents' behaviour and preferences.

- Finally, the fourth section is also concerned with occupant behaviour but focuses on heating. It has five questions, including a question about the type of heating system. Answers to these questions were combined with the third section's answers to create occupant schedules for both heating and cooling seasons.

6.2.2 Participants selection and questionnaire distribution

The final version of the questionnaire was created on the Wenjuan website and connected to the WeChat messaging and calling platform, allowing for easy access to the questionnaire and the possibility for the participants to share it with the people they know if they are willing to do so. The study was conducted according to the Economic and Social Research Council (2012) Framework for Research Ethics guidelines and approved by the Institutional Research Ethics Panel of the University of Nottingham Ningbo China. Any answers containing anything other than the urban areas of Ningbo city in the residential community response box were rejected.

Questionnaire distribution was both online and in-person. In-person distribution was considered important to boost response rates as suggested by Gou et al. (2013). Face-to-face participants were given a choice of filling in the questionnaire online or on paper. Hardcopies of the questions were available for the elderly residents that could not participate in the online questionnaire to avoid the possibility of results being biased towards younger people.

In total, 180 Ningbo urban area residents participated in this survey. Using Equation 5.1 from Chapter 5 and assuming confidence level being 0.05, population proportion 0.5, degree of accuracy equal to 0.1, and population size being 6,084,700 (NATIONAL BUREAU OF STATISTICS, 2021), for the sample to be representative, it should at least contain 96.03 responses. The total amount of responses collected in this research exceeded this amount almost two times, which means higher degree of accuracy. The distribution of participants according to the year of construction period is presented in Table 6.1. 15.6% of participants reported living in buildings constructed before 2002, 47.2% of participants lived in buildings built between 2002 and 2010, 24.4% of residents lived in buildings built in the 2011-2015 period and 12.8% of participants – after the 2015 period. This distribution was very similar to the new residential buildings floor space constructed during different periods discussed in Chapter 5 (18.2%, 34.1%, 25.7%, and 22% respectively). Thus, in both distributions, the biggest portion of building area/residents came from the 2002-2010 construction period and the second biggest from 2011-2015. However, the least represented period for survey participants was the most recent one (after 2015), while for constructed floor space, it was the period before 2002. This difference could be attributed to the delay between the buildings being constructed and occupied, creating a high percentage of recently constructed buildings being unoccupied and therefore not reported on. Based on that, the collected answers were assumed to represent the Ningbo municipality residents' characteristics and occupant behaviour.

	Before 2002	2002-2010	2011-2015	After 2015
Constructed floor space	18.2%	34.1%	25.7%	22%
Reported year of construction	15.6%	47.2%	24.4%	12.8%

Table 6.1 The distribution of actual and reported buildings according to their year of construction.

6.2.3 Questionnaire results and discussion

6.2.3.1 Indoor building form

Questions 1 and 2 in the survey were created to gather data on possible internal layouts of the buildings as the questions concerned the apartment area and the number of residents. Answers to the first question can be used to approximately estimate the number of apartments in a specific building type. In contrast, the answers to the second question can assist in the decision of the number of bedrooms in each apartment and in the creation of occupancy schedules as those depend on the number of people. Finally, the total number of people in a specific building type can be evaluated based on that data.

The averaged results for those two questions were segregated based on the building forms developed in Chapter 5 and are presented in Table 6.2. The average apartment area in LR, MR and both HR building forms was from 110 m^2 to 120 m^2. Villa and terraced areas were considerably bigger with the villa's average area of 272.5 m^2 and terraced apartments of 241.4 m^2.

	Area, m^2	People
Villa	272.5	3.53
Terraced	241.4	2.71
LR	122.3	3.07
MR	117.8	2.95
HRT	119.2	3
HRP	112.8	2.63

Table 6.2 Reported average apartment area and amount of occupants

For the apartment buildings such as LR, MR, and HR it is essential to have common areas used for elevators, staircases, fire escapes, shafts, etc. Since these areas have different occupancy schedules than the indoor space and are usually unconditioned, it is important for accurate energy simulation to include them in the building forms. Currently, there are no precise limitations for common area in residential buildings based on the standards, however, as a rule of thumb, the taller buildings should possess a higher percentage for common areas as more space will be required for the installation of elevators, staircases, and other services in buildings with more people. According to DB33/1006 Zhejiang Provincial Department of Housing and Urban-Rural Development (2017), Zhejiang province has adopted ageing society caring initiatives and promoted the installation of elevators in buildings of 4 floors and taller, and 12 story buildings and taller must have two elevators in each unit. Based on that and based on the average apartment area and the total floor space of each of the created representative form models, the designed indoor layouts are as presented in Table 6.3 and Figure 6.1. The basement areas were not included in the design for simplification purposes. As for the Terraced and Villa building forms did not have common areas, but Villa had unoccupied and unconditioned Garage space which is included in the common area column in the table for its similar thermal and occupancy schedule.

	Common area	Average apartment area, m^2
Villa	8%	291.7
Terraced	0%	254.8
LR	12.6%	128.5
MR	12.8%	106
HRT	18%	121.7
HRP	18.6%	115

Table 6.3 The common area percentage and average apartment area in the developed building form models

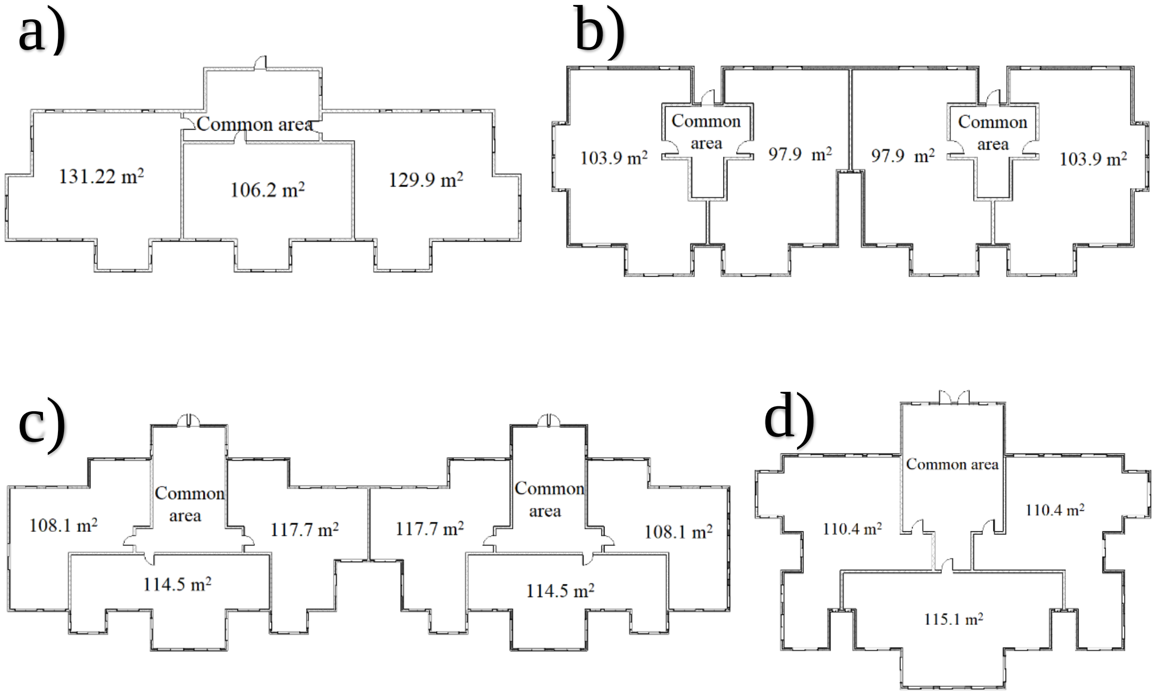


Figure 6.1 Designed indoor layouts of the developed building form models: a) LR, b) MR, c) HRP, d) HRT

Each of the apartments had two bedrooms to accommodate three people. For LR, MR, and HR building forms, bedrooms accounted for around 50% of the total floor area. At the same time, it was around 24% for Villa and Terraced because those apartments were much bigger and had to include stairs in each of the apartments consequently increasing the area requirements. In addition to that, Villa also had a guest bedroom since the average number of people living in Villas was higher than in other building forms. The average living room area was around 30-32 m^2 for all the building forms, which accounted for around 30% for all the block buildings apartments and 12% for Villa and Terraced. The kitchen occupied approximately 10% of the total apartment area in all of the created building forms, and Villa and Terraced apartments were also designed to have dining rooms.

6.2.3.2 Energy consumption

Energy consumption in buildings is driven by many different activities such as lighting, cooking, maintaining a comfortable thermal environment, heating the water, and running other electrical appliances (TV, computers, etc.). While some of these activities might be consistent throughout the year such as cooking, others are more prevalent during a particular month or a season. Heating the space is usually only required during cold winter months (in the northern hemisphere) and cooling is necessary for the hot summer season. This implies that it is highly likely to have increased energy consumption during summer and winter compared to the spring and autumn seasons.

Questions 5, 6, and 7 asked the participants to report on their monthly average electricity and gas consumption bills for each of the four seasons for the previous year. The breakdown of results based on different building forms is presented in Table 6.4 and based on different construction periods in Table 6.5. From the tables, it can be seen that the electricity consumption in spring and autumn is approximately equal. At the same time, during summer and winter, it is much higher with summer electricity consumption being slightly bigger than the winter one. The average monthly gas consumption remains relatively stable during spring, summer and autumn, implying the usage of gas for hot water generation.

	Spring		Summer		Autumn		Winter	
	Electricity RMB	Gas RMB	Electricity RMB	Gas RMB	Electricity RMB	Gas RMB	Electricity RMB	Gas RMB
Villa	198.23	89.45	511.09	97.45	210.54	86.27	462.75	103.64
Terraced	238.57	57	452.86	57	245.71	57	295.71	57
LR	150.72	86.25	276.16	78.39	154.95	87.06	230.47	133.92
MR	175.5	77.97	321.42	79.10	195.21	82	289.39	129.93
HRT	172.39	48	320.44	48.5	177.5	55.5	277.5	61.5
HRP	171.88	62.5	270	67.5	180	62.5	358.13	60

Table 6.4 Reported average electricity and gas bills for each building form

	Spring		Summer		Autumn		Winter	
	Electricity RMB	Gas RMB	Electricity RMB	Gas RMB	Electricity RMB	Gas RMB	Electricity RMB	Gas RMB
Before 2002	149.79	73.65	260.79	70.30	161.79	71.70	182.86	82.17
2002-2010	175.57	87.73	316	80.33	187.99	79.43	277.5	102.61
2011-2015	163.28	67.33	375.29	69.21	177.55	75.67	357.19	133.75
After 2015	165.48	75	286.39	85	147.30	107.1	284.17	196.43

Table 6.5 Reported average electricity and gas bills for each construction period

Comparing electricity consumption in different building forms it can be noticed that overall participants living in Villas and Terraced houses have bigger electricity bills. This can be explained by larger apartment sizes and more people living in the same space for Villa. The smallest average electricity consumption bill for each of the seasons comes from the LR building form. Unlike the electricity, average gas consumption is the biggest in LR and

MR building forms, and the smallest in Terraced and both of the HR building forms. Seasonal variations in gas demand discussed in the previous paragraph are also not present for HR buildings, which could be caused by gas not being used as the main heating source in those building types for safety reasons.

Considering different building construction periods from Table 6.4, the least energy-intensive buildings were built before 2002. This might contradict the idea that little insulation of the building envelope leads to high energy demand. As discussed in Chapter 5, buildings constructed before 2002 were subjected to no standards on thermal performance and therefore often suffered in that regard. However, this inconsistency is most likely caused by different occupant behaviour patterns present in old buildings and newly constructed buildings. Purchase of new living space requires a lot of investment, which means that it is likely that the income of participants living in newer buildings is higher than those living in older buildings. People with higher income tend to possess more electrical appliances and tend to be willing to pay more to sustain a comfortable indoor environment. This hypothesis might be proven (or disproven) in the next subchapter, where the questionnaire results on human behaviour are discussed.

To properly compare the reported total energy consumption in different building forms the results for electricity and gas need to be combined for the whole year and calculated concerning the apartment area. All results must first be converted to consistent units. Thus, the average monthly electricity bills reported in the questionnaire were converted to kWh at 0.538 RMB (State Grid, 2020). The average monthly gas bills were similarly converted to kWh at 2.95 RMB/m^3 (Ningbo China Resources Zingguang Gas Co. LTD., 2021) and a calorific value of 10 kWh (Ishwaran et al., 2017, Ma, 2017, Zou et al., 2018). The total energy consumption for a year was then estimated, assuming the monthly average energy demand in a season to be equal to the energy demand for each month in that season and summing up the electricity and gas results. This amount was further divided by the average apartment area reported for that particular building form. The results for these estimations are presented in Table 6.6.

	Villa	Terraced	LR	MR	HRT	HRP
Energy demand, kWh/m^2	41.76	37.67	67.76	76.94	61.77	70.28

Table 6.6 Reported average energy usage intensity for each building form.

Based on the table above, despite the Villa and Terraced buildings residents reporting the biggest electricity and gas bills, their energy demand per meter square is actually smaller than the ones presented by the block buildings’ residents. This can be explained by a larger area and consequently greater number of rooms, many of which (considering the number of occupants is approximately the same as in other building forms) are not simultaneously occupied. Among all the building forms, residents of MR buildings stated the highest energy demand per meter square. As it was discussed in Chapter 5, MR and taller buildings do not have any representative buildings built before 2002, which makes all of these buildings relatively new and newer buildings, according to Table 6.6, have higher energy demand.

6.2.3.3 Heating and cooling behaviour

Human behaviour in buildings is a natural driver for energy consumption. Building energy performance and occupants' behaviour are mutually intertwined as, on the one hand, if the residents are not satisfied with the indoor environment, they tend to change it by using building services. On the other hand, if the building performs its best at providing a comfortable environment, the occupants tend to be satisfied and do not interfere with the heating, cooling, lighting and other systems. Hoes et al. (2009) define human behaviour as "the presence of people in the building, but also as the actions users take (or not) to influence the indoor environment".

Occupant satisfaction, however, is highly subjective and can be biased as it depends on many personal factors such as age, gender, complexion, previous thermal experiences, income, culture, etc. (Kim et al., 2013, Schweiker et al., 2018, Albuainain et al., 2021, Fanger, 1970, Fanger and Toftum, 2002, Frontczak and Wargocki, 2011) Some of these variables cannot be fully taken into account even on average when simulating building energy consumption on a city scale (such as age, gender, and complexion). Others, however, should be considered, and the thermal and occupant schedules need to be adjusted according to the local background.

Questions 8-16 were designed to collect data on residential buildings users' behaviour to analyse the heating and cooling equipment that Ningbo residents use in their homes and the patterns of heating and cooling systems usages. The results are presented in the following sections with Section 6.2.3.3.1 focusing on cooling behaviour in summer and Section 6.2.3.3.2 focusing on heating behaviour in winter.

6.2.3.3.1 Cooling behaviour in summer

According to MoHURD (2015)**,** the average hottest month's temperature in Ningbo is around 30°C. With these hot temperatures and high humidity caused by the nearby sea, many Ningbo residents install split air conditioning units (further referred to as AC for simplification) in their homes to maintain comfortable indoor temperatures. Occupants cooling behaviour highly depends on personal preferences as well as the amount of AC units installed in each apartment, therefore, a local context for both of these variables needs to be studied and analysed.

6.2.3.3.1.1 Air Conditioning (AC) units

Table 6.7 and Table 6.8 present answers to question 8 inquiring about the amount of AC units installed in participants' apartments. Based on Table 6.7, each apartment in all of the building forms has on average slightly less than three AC units. Terraced buildings have the least average amount of 2.57, while all the other building forms have around 2.9 AC units. A strong correlation can be observed between the building construction period and the average amount of ACs in apartments with more AC units being installed in newer buildings per apartment. These results prove the first part of the hypothesis discussed before that reported higher energy demand in newer buildings can potentially be caused by the greater amount of appliances being installed.

	Villa	Terraced	LR	MR	HRT	HRP
AC units	2.86	2.57	2.90	2.93	2.83	2.85

Table 6.7 Reported average amount of AC installed for each building form

	Before 2002	2002-2010	2011-2015	After 2015
AC units	2.39	2.75	3.08	3.22

Table 6.8 Reported average amount of AC installed for each construction period

6.2.3.3.1.2 Preferable time of cooling

Question 9 in the distributed questionnaire inquired about the most common time when occupants used air conditioning. The participants were given 6 options from which they could select all the suitable answers according to their own preferences: ‘Never’, ‘Night’, ‘Morning (before work)’, ‘Lunch break (midday)’, ‘Evening (after work)’, and ‘All day’. The results presented in Figure 6.2 show, that none of the total participants chose ‘Never’ as the answer, implying that all of the participants used AC for cooling in summer. 21.79% of respondents specified using air conditioning all day, the votes of these participants were further added to the Night, Morning, Lunch, and Evening replies for better presentation.

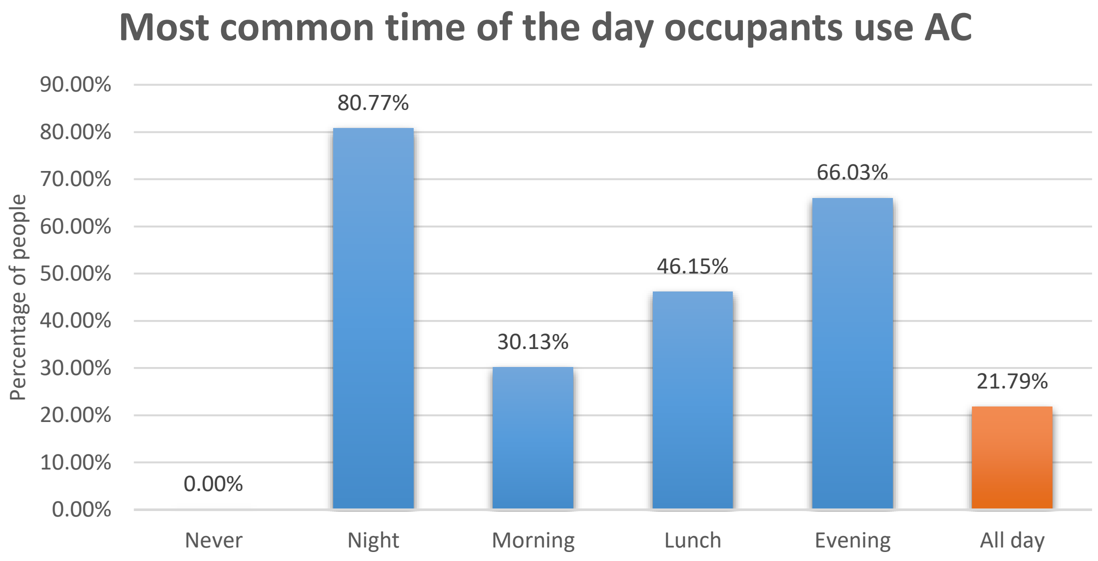


Figure 6.2 Most common reported time of the day occupants use AC for cooling

Thus, the most common time of the day when residents chose to use air conditioning in summer was night, the second most common was evening. The high response rate for night and evening could be explained by high occupancy rates during these times of the day: a majority of working adults and studying children and teenagers were coming to their apartments after work or school and stayed overnight. According to the respondents' replies, the least common time of the day to use cooling was morning with 30.13%. While the occupants were still present in the residential buildings in the mornings before school and work, both the outside and the inside temperatures at that time were usually lower than in the afternoon. The building materials had also been cooled down during the night (driven by the thermal inertia of materials), lowering the radiant temperature too. Therefore, many residents might feel contented with the thermal environment and chose not to use air conditioning. Based on this, it can be said that the cooling system usage is mainly dependent on the occupancy and the temperature and that the vast majority of occupants use cooling at night.

6.2.3.3.1.3 Frequency of cooling

Questions 10 and 11 of the questionnaire asked about the frequency of using AC during night-time and day-time respectively. The participants were given four answers to choose from: Never, The hottest days (up to 2 weeks), Half of the summer, and All of the summer. Figure 6.3 (a) shows all of the participants used cooling during the night at some point during the year. Almost 60% of them used it during the whole summer, almost 30% used it for half the summer, and 14.1% during the hottest days only. Figure 6.3 (b) shows, that overall cooling was used less frequently during the day, as nearly 2% claimed to never use cooling in a day-time, only 40% stated using it throughout the whole summer, slightly less than 34% used it for a half a summer, and nearly 25% turned on AC only for up to two weeks.

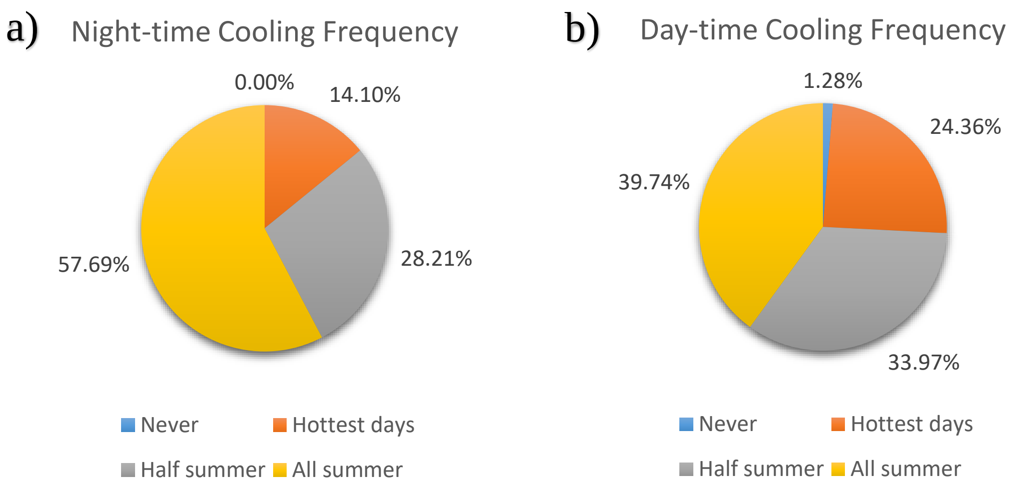


Figure 6.3 Reported frequency of using AC for cooling a) during night-time; b) during day-time

Comparing different building construction periods and the occupants cooling behaviour presented in Table 6.8, it could be noticed that overall, the number of occupants specifying that they were cooling their apartments for the whole summer was greater for the new buildings than for the old ones. At the same time, the percentage of people using cooling only during the hottest days went down for new buildings. This tendency was especially straightforward with night-time cooling. These results supported the possibility of higher reported energy demand in newer buildings being caused by a different occupancy behaviour in them.

	Before 2002		2002-2010		2011-2015		After 2015	
	Night-time	Day-time	Night-time	Day-time	Night-time	Day-time	Night-time	Day-time
Never	0.00%	0.00%	0.00%	0.00%	0.00%	2.70%	0.00%	4.35%
Hottest days	33.33%	50.00%	12.50%	14.29%	10.81%	24.32%	4.35%	17.39%
Half summer	27.78%	33.33%	30.36%	35.71%	37.84%	40.54%	17.39%	30.43%
All summer	38.89%	11.11%	57.14%	50.00%	51.35%	30.77%	78.26%	47.83%

Table 6.9 Reported frequency of using AC for cooling for each construction period

6.2.3.3.2 Heating behaviour in winter

Ningbo belongs to China's HSCW climate zone with the average coldest month's temperature being around 5°C and occasional below-zero temperatures and snow. Since the location belongs to the south part of China, no central heating is being provided in the residential buildings according to the thermal design code (MoHURD, 1993). However, the cold winter temperatures and high wind speeds cause an uncomfortably cold indoor environment, driving the occupants to use personal radiators, split air conditioners, or other equipment for heating. Similarly to the occupants cooling behaviour, local heating behaviour and the heating equipment need to be studied and analysed for accurate estimation of building energy performance.

6.2.3.3.2.1 Heating system

Question 12 in the questionnaire required the participants to select the type of heating system that they use in their apartments. The available options were: 'Do not use', 'Radiators (or electric fans)', 'Air conditioning units', 'Floor heating', 'Other'. If the respondents chose option 'Other', they were redirected to question 13 asking to specify the heating equipment that they use. Among all of the participants only 4 chose the 'Other' option, three of which stated the brand of their radiators (and consequently were attributed to radiators answers), one stated using electric blanket heaters and was included into the 'Do not use' category of respondents since they were not using any space heating equipment.

Table 6.10 presents the replies to question 12 grouped based on the residents' building forms. Analysing all of the collected information, the most common heating equipment based on the results was AC (varies from 40% to 60%), and the least common one was floor heating (from 0% to 15%). In addition to that, based on the results displayed in Table 6.11, floor heating was used more frequently in the newer buildings. Meanwhile, the highest percentage of participants specifying that they did not use heating systems came from buildings constructed before 2002, further supporting the hypothesis that higher energy consumption in newer buildings is driven by occupants' behaviour.

	Villa	Terraced	LR	MR	HRT	HRP
Do not use	42.9%	28.6%	10.4%	10.7%	9.1%	7.7%
Radiators	14.3%	14.3%	28.4%	25%	27.3%	30.8%
AC	42.9%	42.9%	52.2%	57.1%	54.5%	46.2%
Floor heating	0%	14.3%	9.0%	7.2%	9.1%	15.4%

Table 6.10 Reported heating system type for each building form

	Before 2002	2002-2010	2011-2015	After 2015
Do not use	29.4%	12.3%	14%	4.3%
Radiators	35.3%	26.3%	21.6%	30.4%
AC	35.3%	52.6%	51.4%	52.2%
Floor heating	0%	8.8%	13.5%	13.1%

Table 6.11 Reported heating system type for each construction period

6.2.3.3.2.2 Preferable time of heating

Similarly to Question 9, Question 14 inquired about the most common time of the day when occupants use heating. The participants were given the same 6 options from which they could select all the suitable answers: ‘Never’, ‘Night’, ‘Morning (before work)’, ‘Lunch break (midday)’, ‘Evening (after work)’, and ‘All day’. In the same way as before, respondents’ votes specifying using heating during the whole day were added to the Night, Morning, Lunch and Evening replies for better presentation.

Figure 6.4 displays results to this question.18.69% of participants specified using heating during the whole day, and 10.28% of participants claimed to not use heating at all. The most frequently stated time of the day when occupants used heating in their apartments was night and second to that evening. These results were alike the occupant behaviour results found for cooling: time of the day when the occupancy rates were expected to be high the heating requirements were high as well. Overall, the heating demand was reported to be less than the cooling demand, since option ‘Never’ was not selected by respondents in the “cooling behaviour in summer” part of the questionnaire, while more than 10% selected it for heating. All of the other options were chosen less frequently too, with a difference varying from 3% to 25%. The only exception to that was “Morning (before work)’ as it had a 30.13% of selection rate in the cooling part of the questionnaire and 30.84% in the heating part of the questionnaire. As discussed before, the indoor temperatures in the early morning could potentially be very low compared to the rest of the day, as the outside temperatures were low and the building envelope cooled down at night. This could drive the occupants to use the heating system to bring the indoor temperature up to a comfortable range. Based on these results, it can be said that the heating is mainly dependent on a combination of occupancy and temperature and that the majority of occupants use heating at night. Both cooling and heating were used by residents on a part-time part-space basis.

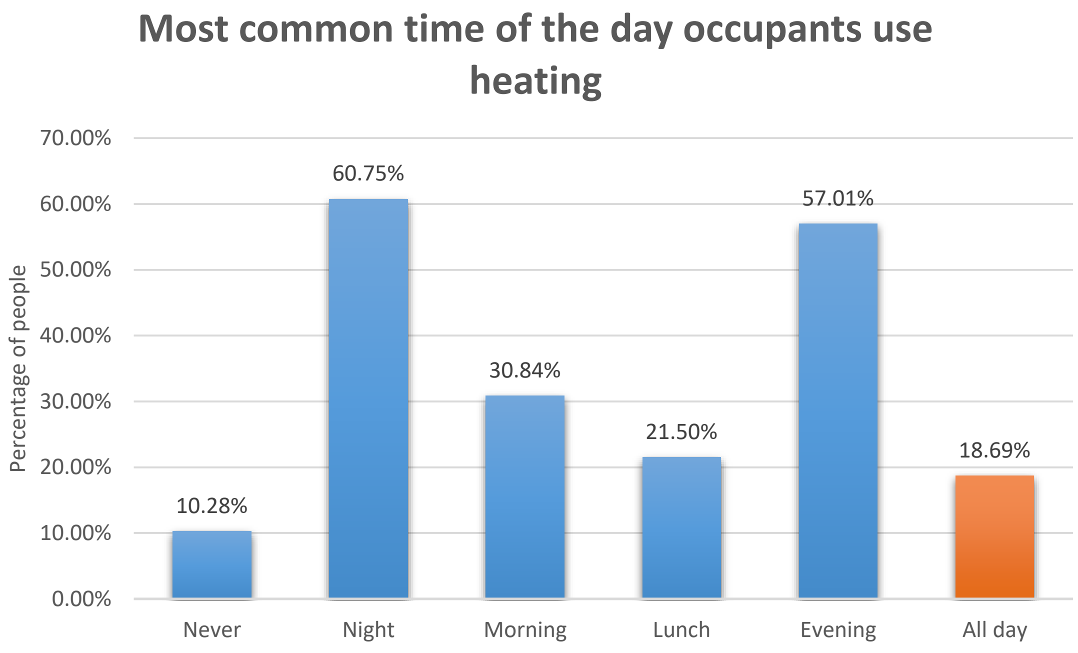


Figure 6.4 Most common reported time of the day occupants use heating

6.2.3.3.2.3 Frequency of heating

The last two questions of the questionnaire focused on the frequency of using heating during night-time and day-time respectively. The participants were given four answers to choose from: Never, The hottest days (up to 2 weeks), Half of the summer, and All of the summer. Figure 6.5 displaying the replies to these questions revealed that 10.28% did not use heating during the night and almost 15% did not use it during the day. The majority of replies for both night-time and day-time heating frequency came from participants reporting using heating only during the coldest of days (33.64% and 36.45% respectively). As for the two groups of respondents specifying the usage of heating for half of winter and the whole winter, they represented approximately equal parts of the rest of the replies (28% each for night-time and almost 24% each for day-time). Similarly to the cooling frequency replies, these results showed that heating during the day was used less frequently than during the night, probably because of the lower occupancy rate during the day and due to higher daytime indoor temperatures. Overall, heating was used less frequently than cooling, which could be explained by the high value of clothing insulation worn by HSCW climate zone residents (Yan et al., 2019).

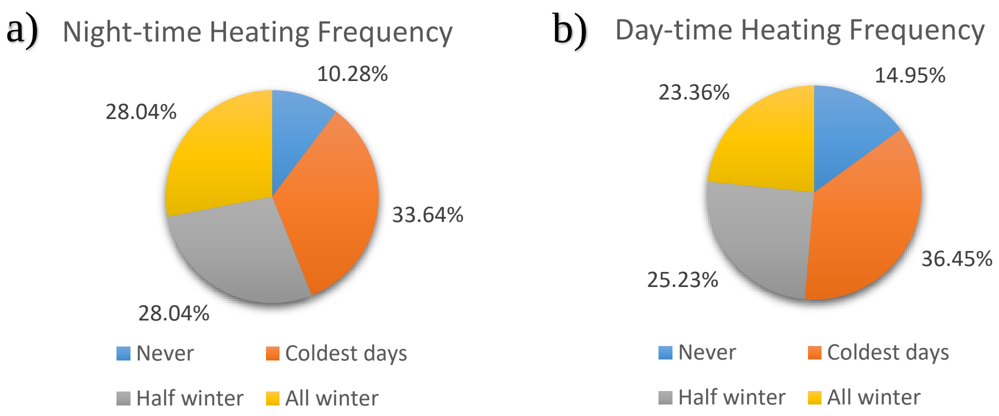


Figure 6.5 Reported frequency of using heating a) during night-time; b) during day-time

Table 6.12 presents the night-time and day-time heating frequency data grouped based on the different building construction periods. Based on it, the residents living in buildings built between 2002 and 2010 reported using heating the most frequently as they accounted for the highest percentages of using heating for half of the winter and during all of the year for both night-time and day-time heating. This could be explained by a combination of relatively low building energy performance, since the first energy standards were not as strict as the latter, and already changing occupant behaviours towards more consuming patterns.

Among the four of the groups' occupants of buildings built Before 2002 and After 2015 used heating the least frequent with 36.36% of the ‘Before 2002’ group specifying to never use heating during day-time and 26.67% of residents coming from built after 2015 buildings never using heating in the night-time. The biggest parts of those two groups’ residents also used heating only during the coldest winter days. Overall, the reported behaviour of occupants living in buildings constructed before 2002 was the most energy-saving because more than 80% of them never use heating or only for up to two weeks in a year. As discussed before, this conservative behaviour could be explained by a potentially lower income of that group of citizens. Meanwhile, the reason for the reported heating frequency usage being low for residents from the 'After 2015' buildings group was possibly better building envelope performance driven by more strict building energy standards.

	Before 2002		**2002-2010**		**2011-2015**		**After 2015**	
	Night-time	Day-time	Night-time	Day-time	Night-time	Day-time	Night-time	Day-time
Never	9.09%	36.36%	7.69%	7.69%	8.70%	17.39%	26.67%	20.00%
Coldest days	72.73%	45.45%	23.08%	30.77%	34.78%	43.48%	26.67%	46.67%
Half winter	9.09%	18.18%	38.46%	35.90%	30.43%	26.09%	26.67%	13.33%
All winter	9.09%	0.00%	30.77%	25.64%	26.09%	13.04%	20.00%	20.00%

Table 6.12 Reported frequency of using heating for each construction period

6.3 Occupant behaviour schedules creation

The analysis of heating and cooling behaviour in Ningbo city showed that the city residents adjusted their energy consumption behaviours in accordance with the local context. The main difference between the commonly used occupant behaviour schedules present in many building energy simulation software and the occupant behaviour reported in the questionnaire was the fact that both the heating and cooling were used on a part-time and part-space basis. These findings were similar to other research (Wang et al., 2015b, Yu et al., 2009a, Yan et al., 2019). The absence of central heating, inadequate building energy performance which led to high energy consumption if the heating or cooling were being used, and consequently potentially high energy bills encouraged residents to switch off heating and cooling in rooms that were not occupied at that moment.

Analysing the collected data on winter and summer occupant heating and cooling behaviours allowed for the creation of locally-adjusted human behaviour profiles used further for the building energy simulation purposes. Though, the results showed that the heating and cooling preferences might slightly vary among the buildings mostly depending on the building construction period, the final occupant behaviour schedules were created the same for each building form and each construction period based on the average assumption for simplification purposes.

6.3.1 Occupancy profiles

Energy consumption in buildings is highly dependent on the presence of people and their actions. Many activities, such as lighting, cooking, equipment usage, and, in conditions observed in Ningbo, heating and cooling are mainly used when the people are present and where they are present. Therefore, the occupancy profiles have to be created differently for different rooms based on their usage schedules so that all the other energy usage schedules can rely on them.

Figure 6.6 displays the occupancy profiles of weekdays and weekends for the Bedroom, Living room, and Kitchen developed in IES-VE. They were developed based on the measured data from Wang et al. (2015b) with slight changes to accommodate for the inclusion of Kitchen (Kitchen and Living room in this research divided the occupancy of Living room in Wang’s paper). In addition to that, this study implemented a linear function to present the possibility of occupancy unlike the on-off function used previously. It was decided to develop different profiles for weekdays and weekends to more closely follow the common working and studying day schedule, while still accounting for a possibility of having longer and higher occupancy during weekends. The developed weekend profiles for each of the rooms were also used for the holidays including the Spring Festival holiday (Chinese New Year) set between January 25th and February 10th.

Thus, the Bedroom was set to be primarily used during the night with a little possibility of occupants being present during and after the lunch break (to account for elderly people). The Living room was mainly occupied in the evening both for the weekday and weekend, had a small probability of being occupied in the morning before lunch on the weekday (to account for the elderly) and a high probability at the weekend. The Kitchen occupancy profile was developed to be occupied during the meal times; since almost half of questionnaire participants reported using the cooling during the lunch break (discussed in Section 6.2.3.3), a high possibility of residents being present was set for lunch break both during weekday and weekend.

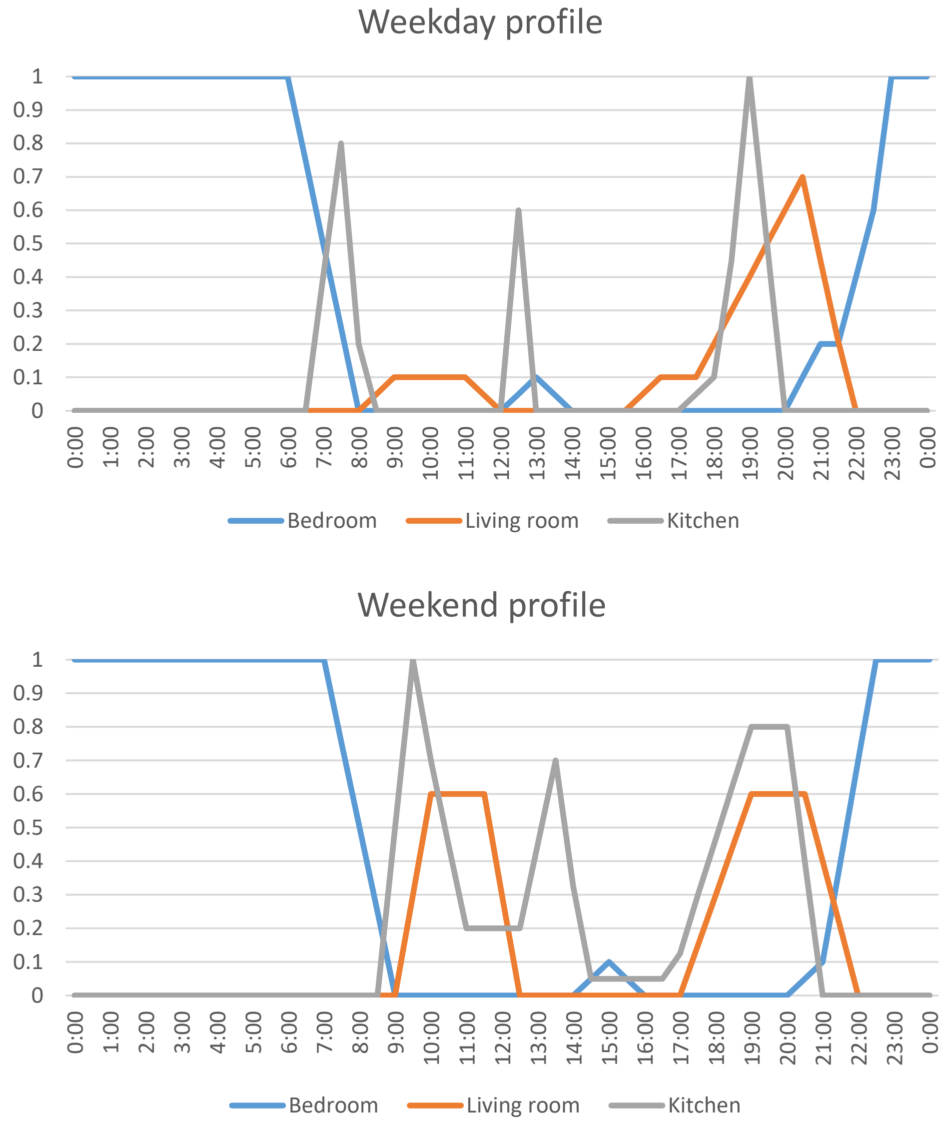


Figure 6.6 Occupancy profiles of weekdays and weekends in three types of rooms

6.3.2 Temperature profiles

The range of indoor temperatures considered to be comfortable can be different from one resident to another depending on many personal factors and preferences. However, temperatures maintained during heating and cooling seasons influence the overall energy consumption in buildings. Therefore, considerations should be taken regarding the temperature profiles input in the simulation software.

In this research, the minimum requirements for an indoor comfortable thermal environment established in the national and local standards (Ministry of Construction of PRC, 2001, Ministry of Construction of PRC, 2010, Ministry of Construction of Zhejiang, 2015) was used as the basis for temperature profiles creation. According to the standards, the maximum comfortable indoor temperature in summer was 26°C, while the lowest comfortable indoor temperature in winter was 18°C. Based on that, the cooling system was set to be used when the indoor temperature exceeded 26°C and when the room was occupied. Since the majority of questionnaire participants stated using cooling overnight, this temperature was maintained during night time as well. For the heating, however, it was decided to have different temperatures for when the occupants are active and when they are asleep for two reasons. The first reason is that the bedclothes' insulation is much higher than the indoor cloths' and therefore the occupants can in theory withstand lower indoor temperatures while asleep. The second reason supports the first theoretical one being the biggest portion of all questionnaire participants (33.64%) stated using heating for only the coldest winter days (i.e. up to two weeks). This means, that during the main part of the winter when the outside temperatures vary between 5°C and 15°C the majority of occupants do not use night-time heating. Based on that, the indoor temperature when the occupants were awake was set to be 18℃ and when they were asleep to be 10℃, which is similar to other research (Wang et al., 2015b).

6.4 Reference buildings energy model

6.4.1 Heating, Cooling, DHW systems setup

Heating and cooling energy demand in buildings is highly dependent on the heating and cooling system types installed in the building, their performance as well as the usage schedule. Since based on the questionnaire results the main heating system type was reported to be AC, split air conditioners were used in the energy model as both heat and cold sources. The coefficient of performance (COP) of these systems was set in accordance with the design standards for energy efficiency in buildings as being equal to 1.9 for heating and 2.3 for cooling (Ministry of Construction of PRC, 2001, Ministry of Construction of PRC, 2003, Ministry of Construction of PRC, 2010). The cooling system usage schedule was set to be continuously maintaining the temperature of 26℃ whenever the occupants were present in the room (dependent on the occupancy schedules developed in the previous chapter). The heat rejection of the pump and fan was set at 10% as suggested by the software. The temperature maintained by the heating system, as discussed in the previous chapter, was varied between 18℃ when the occupants were present and awake and 10℃ when the occupants were present and asleep. The sleeping schedule was set from 11 pm to 6:30 am during the weekday and from midnight to 8 am for the weekends and holidays. When the occupants were not present the heating system was switched off. In addition to the temperature control, the cooling and heating systems were set to maintain the humidity between 30% and 80% as was suggested by the standards (Ministry of Construction of PRC, 2001, Ministry of Construction of PRC, 2003, Ministry of Construction of PRC, 2010).

The HSCW area in China has no centralized DHW supply, thus, the residents have to rely on individual systems. In this research, the main DHW system was set as the electric water heater with second-grade efficiency (82%) as was suggested in Liu et al. (2019). The storage volume was assumed to be 60 litres with storage losses of 0.0047 kWh/(l*day) (default software value). The mean inlet cold water temperature was 10℃ and hot water supply temperature 60℃. The hot water usage profiles were created for the bathroom and kitchen to provide 50-70 l/person/day in total as was suggested by An et al. (2016) and Liu et al. (2019).

6.4.2 Internal gains

The internal gains of energy in the building included lighting, equipment and residents. The average load created by lighting and equipment was set as described in the design standards for energy efficiency in buildings to be 6 W/m^2 and 4.3 W/m^2 accordingly (Ministry of Construction of PRC, 2001, Ministry of Construction of PRC, 2003, Ministry of Construction of PRC, 2010). While the lighting energy load was included in every room of every created building form, the equipment load was excluded in the common areas (LR, MR, HRT and HRP), garage (Villa) and halls (all of the building forms). The artificial lighting usage profile was dependent on two variables: the presence of residents in the room (occupancy schedule) and the amount of natural lighting available. The limiting amount of natural illuminance for artificial lighting to be switched off was set as 300 lux according to CIBSE guides (Chartered Institution of Building Services Engineers, 2006). Below that point, a dimming profile was introduced from 200 lux to 300 lux to reflect the occupants' ability to switch on only the local lights (instead of using all of the available lights) necessary for the tasks they performed in the room. The equipment usage schedules also depended on the residents' presence with 20% of the maximum load as the background load for when the occupants were either absent or present and sleeping.

The maximum sensible and latent heat gains generated by people were adapted from CIBSE Guide A depending on the room types and most likely activities being performed there (Chartered Institution of Building Services Engineers, 2006). Table 6.12 describes the room types and assigned internal gains produced by people. Similarly to the lighting and equipment usage profiles, the variation profile of these gains were connected to the occupancy schedules in the rooms.

	Sensible heat gain, W/person	Latent heat gain, W/person
Dining room / kitchen	75	55
Hall	110	185
Living room	70	45
Bathroom	110	185
Study	75	55
Bedroom	65	30

Table 6.13 Sensible and latent heat generated by occupants in different room types

6.4.3 Building ventilation

Typically, the split air conditioning units do not provide the fresh air flow into the building and there are no other auxiliary ventilation systems present in residential buildings of

Ningbo except for toilet extracts. Therefore, the main air supply mechanism was set as the local ventilation units, such as windows. Thus, the total air flow in the building was set to be comprised of three parts: building envelope infiltration, air permeability (crack flow for windows and doors), and window opening.

The infiltration was set constant at a rate of 1 ach according to the design standards for energy efficiency in buildings (Ministry of Construction of PRC, 2001, Ministry of Construction of PRC, 2003, Ministry of Construction of PRC, 2010). Similarly, the air permeability was also derived from the local standards (discussed in Section 5.4) and transformed into crack flow coefficient based on the following formula:

$$q = CL(\rho_0/\rho)^{0.5}\Delta P^{0.6} \tag{6.1}$$

Where q is the air flow through the crack (l/s), C is the crack flow coefficient (l/s*m*$Pa^{0.6}$), L is the length of the crack (m), P is the density of air entering the crack (kg/m^3), ρ_0 is a reference air density equal to 1.21 kg/m^3, and ΔP is the pressure difference across the crack (Pa) (IES, 2011b).

Different window exposure types were assigned for different windows on different building forms to represent the most accurate wind pressure coefficients (reference to

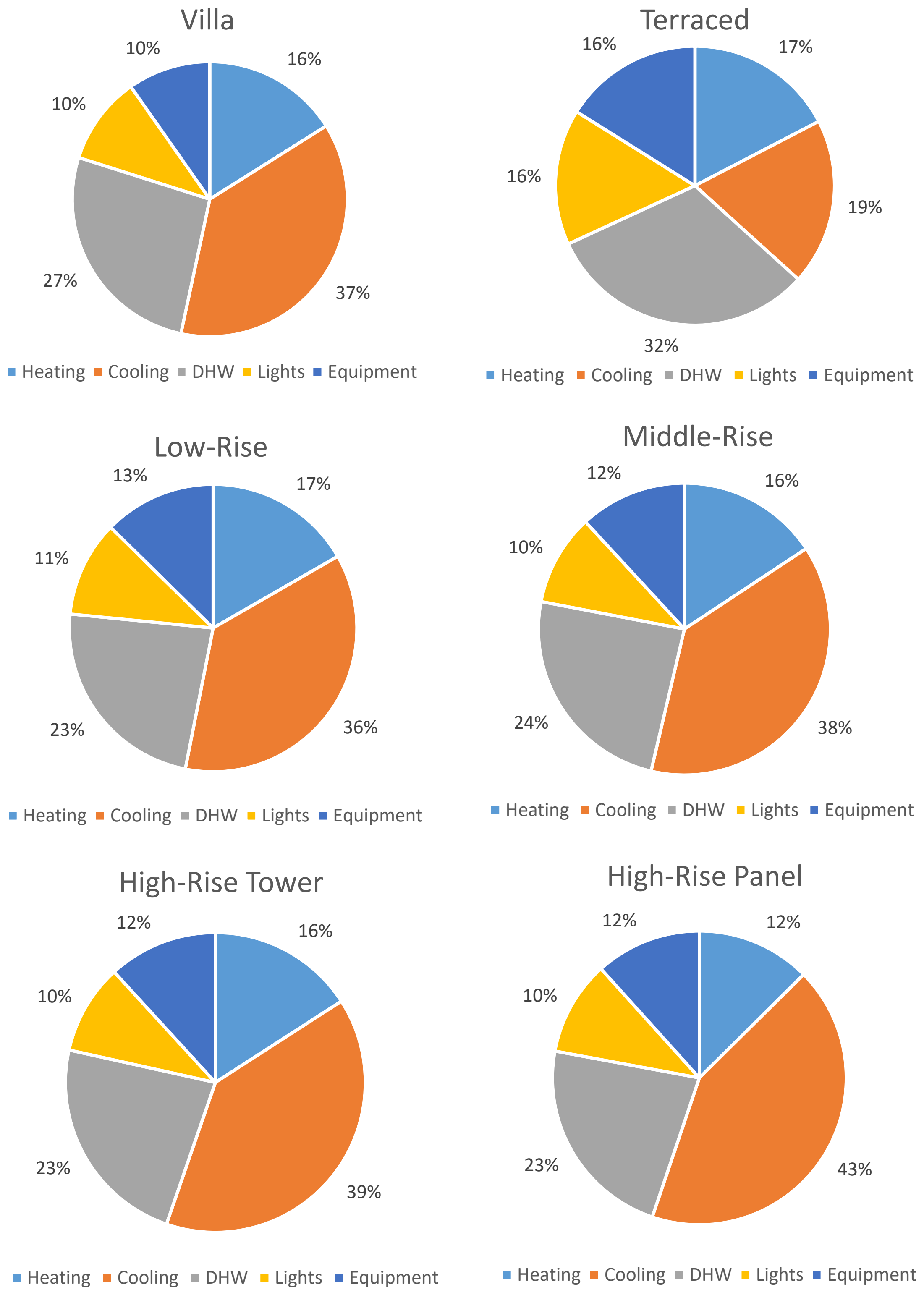
MacroFlo Calculation Methods manual (IES, 2011a) for further information). In the case of the Villa building form, the allocated window exposure type was a '1:1 semi-exposed wall' describing a building with approximately equal length of the façade sides. For the Terraced building form, the selected exposure type was either '2:1 semi-exposed long wall' representing windows on the long side of the rectangular building or '2:1 semi-exposed short wall' for the short façade side. As for the rest of the building forms 'High-rise semi-exposed wall' with different window heights to the height of the building ratio was chosen. The opening category of windows was set as 'sliding/roller door' and an openable area of 30% of the total window area; the crack length was set as 120%.

The developed window opening behaviour was dependent on three variables: the occupancy, indoor temperature and cooling profile. Thus, the windows were closed if the inside temperature was below 18°C or if the air cooling was running. The windows were open if the occupants were absent and the indoor temperature was above 18°C, as well as when the occupants were present and the indoor temperature varied between 18°C and 26°C.

6.5 Energy simulation results and building typologies validation

Different IESVE software in-built applications were used to perform solar shading, day lighting, electric lighting, multi-zone air movement and thermal analysis for the final building energy consumption simulation.

The overall results, presented in Figure 6.7 and Table 6.13, show that the main part of energy demand in simulated buildings came from building cooling (from 19% up to 43%); the second most energy-consuming activity in these buildings was domestic hot water production (from 23% up to 32%); the third place was taken by building heating activities (from 12% up to 17%). The heating and cooling energy consumption averaged by floor area as well as the DHW energy demand per household for LR, MR, and both HR building typologies were similar to other research (Deng et al., 2019, Hu et al., 2016, Li et al., 2019, Liu et al., 2019, Wang et al., 2015b). For Villa and Terraced building typologies the greater floor area per household influenced these calculations resulting in smaller E_c and E_h per meter square than in other scientific papers.



Villa

Terraced

Low-Rise

Middle-Rise

High-Rise Tower

High-Rise Panel

Figure 6.7 Breakdown of building energy consumption simulation results by energy type

	Year of construction	E_h	E_c	DHW	Light	Equip	E_h/m^2	E_c/m^2	DHW/hh
Villa	Before 2002	2.539	5.897	4.194	1.6376	1.5398	8.01	18.60	4193.6
	2002-2010	2.219	5.796	4.194	1.6406	1.5398	7.00	18.28	4193.6
	2011-2015	1.868	5.726	4.194	1.6384	1.5398	5.90	18.06	4193.6
Terraced	Before 2002	8.635	9.614	15.62	7.8317	8.0069	6.78	7.55	3124.06
	2002-2010	7.792	9.196	15.62	7.9724	8.0069	6.12	7.22	3124.06
	2011-2015	6.71	8.750	15.62	7.9724	8.0069	5.27	6.87	3124.06
LR	Before 2002	31.061	67.759	43.638	20.0942	23.5194	11.11	24.24	2077.98
	2002-2010	28.572	66.99	43.638	20.0942	23.5194	10.22	23.96	2077.98
	2011-2015	26.913	66.626	43.638	20.0942	23.5194	9.63	23.83	2077.98
MR	2002-2010	94.393	228.2	146.31	60.8368	71.2751	11.72	28.34	1925.16
	2011-2015	89.14	227.72	146.31	60.8574	71.2751	11.07	28.28	1925.16
HRT	2002-2010	127.78	316.97	186.51	78.2172	94.8949	10.59	26.27	2072.33
	2011-2015	122.38	316.5	186.51	78.2172	94.8949	10.14	26.24	2072.33
HRP	2002-2010	202.08	685.14	365.3	167.1252	187.7422	9.28	31.46	2029.45
	2011-2015	200.61	684.24	365.3	167.1252	187.7422	9.21	31.41	2029.45

Table 6.14 Breakdown of building energy consumption simulation results by energy type

The obtained results for all the building forms and construction years were compared with the average energy usage intensity results collected from the questionnaire in Chapter 6 for validation purposes. All the results were presented in Table 6.14.

	Year of construction	Simulated		Questionnaire
		Total energy, MWh	EUI, kWh/m^2	EUI, kWh/m^2
Villa	Before 2002	15.8074	49.9	41.8
	2002-2010	15.3887	48.5	
	2011-2015	14.9654	47.2	
Terraced	Before 2002	49.7081	39.0	37.7
	2002-2010	48.5877	38.1	
	2011-2015	47.06	36.9	
LR	Before 2002	186.0705	66.5	67.7
	2002-2010	182.8158	64.7	
	2011-2015	180.7899	67.0	
MR	2002-2010	601.0159	74.6	76.9
	2011-2015	595.3062	73.9	
HRT	2002-2010	804.3773	66.7	61.8
	2011-2015	798.5	66.2	
HRP	2002-2010	1607.383	73.8	70.3
	2011-2015	1605.0188	73.7	

Table 6.15 Comparison of reported and simulated building energy usage intensity

From the table, it could be seen that the greatest difference in energy consumption between the simulated and reported by questionnaire was in Villa building form. These discrepancies could be attributed to the highly occupancy-driven energy demand patterns in buildings (Hoes et al., 2009, Gill et al., 2010, Wang et al., 2015b). Since, unlike other building forms, Villa presented the energy demand of a single-family, the energy consumption in villas could vary greatly from case to case. In this situation, Villa presented unique typology patterns different from all the other building forms where the family-to-family energy variations were averaged out. These differences might have possibly been exacerbated by the fact that initially the energy model calibration was done on LR building form models to better reflect the prevailing block type buildings. After that, the same energy and occupancy patterns were used in all the building form models including Villas.

For all the other building forms the simulated results had a similarity of more than 90% with the reported ones. Nonetheless, the results were thought to be representative of all the building forms and the building typologies being a reliable tool for residential building retrofit scenarios evaluation.

6.6 Conclusion

Accurate and reliable building energy simulation requires accurate human behaviour input and data on actual building energy demand to validate the simulation. Thus, the first part of this chapter discussed the development, distribution, results, and outcomes of the questionnaire that focused on the occupants' interaction with their heating and cooling systems and their energy bills in Ningbo city. The questionnaire was distributed both online and personally and represented the urban area of Ningbo municipality.

The results obtained from this questionnaire were used in the second part of this chapter to produce occupancy profiles for the building energy models creation representative of local behaviour. The other variables used to set up the reference building energy models were outlined and objectified here. The developed building typologies were used to perform building energy demand simulation. The EUIs obtained via simulation were further compared to the collected through the questionnaire. The results showed high agreement between those two and the developed typologies being a reliable tool for energy consumption estimations.

Building typologies created and verified in this chapter can be used in future research for indoor environment evaluation, forecast of climate change adaptation and mitigation by buildings, retrofit assessment, policy guidance, decision-making, etc. In this research, they are used to assess various individual retrofit measures and their combinations to determine the most economic and environmentally beneficial options for different building types present in Ningbo’s residential building stock. This evaluation is performed in Chapter 7.

7 Chapter 7. Building retrofit measures. Results and discussion of application of EE assessment framework.

7.1 Introduction

The environmental and climate concerns urge decarbonisation and energy demand decrease in the residential building sector throughout the world, including Ningbo. The technological progress in buildings and building services provides architects, designers and engineers with a diverse variety of building retrofit measures to address these issues. However, these measures need to be carefully evaluated to perform well both in any certain climate and on a specific building type with a specific local building usage pattern. In addition to the retrofit technologies interacting with the building and its habitants, these technologies can also interact with each other. Taking into account that the design of any building retrofit activity involves consideration of many financial and environmental parameters such as IIC, LCC, $S_{\Delta E}$, PBP, ΔGHG^r, energy demand decreases, retrofit technologies' embodied energy, etc., different retrofit measures' interaction adds another layer of difficulty to this already challenging and demanding activity.

The initial step in any building retrofit scenarios assessment research is to simulate the energy consumption of the studied non-retrofitted buildings, which has been done in the previous chapter. This information is necessary to proceed with different retrofit actions simulations for later comparison of the baseline and retrofitted building's energy consumption results. Based on this comparison it can be decided whether or not the evaluated retrofit measures are useful, beneficial, affordable, and sustainable.

This chapter outlines the individual building retrofit measures suggested based on the literature review executed in Chapter 2 for evaluation of their performance on Ningbo's residential building stock. Economic and Environment Score assessment framework is applied on the developed in previous chapters building typologies to determine the most optimal building retrofit scenario for each building typology. First, every individual retrofit measure is simulated and evaluated and then combinations of retrofit measures are applied in a ranked order based on their established priority with an economic viability evaluation on each step. As a final result of this analysis, economically and environmentally beneficial retrofit packages for Ningbo city residential buildings can be identified and proposed with analysis of their financial and GHG emissions impact on the studied buildings.

7.2 Retrofit measures outline

7.2.1 Building envelope upgrade

Increasing the insulation properties of building envelope elements is one of the most common retrofit procedures since it is considered to be an effective method to improve building energy performance (Eames et al., 2014, Riley, 2011, Parker, 2010, Shah, 2012, Burton, 2012). Usually, the upgraded elements are the external walls, roof, windows and ground floor. This research attempts to assess and develop retrofit options suitable for the unique local indoor conditions created by the part-time part-space heating and cooling occupants' behaviour, therefore, the addition of insulation on the external walls, roof, ground floor as well as internal floors/ceilings and the internal walls was considered. Different options for windows replacement were included as well.

7.2.1.1 External walls

The insulation material used in this research for external walls was EPS (expanded polystyrene) for its high thermal resistivity, lightweight and water resistivity properties. According to Pan et al. (2012), the best insulation thickness for external walls in the HSCW climate zone was 26 mm, increase in insulation beyond this amount led to an increase in cooling demand driven by the south façade solar gains. Yu et al. (2009b) stated that for Shanghai (which had very similar climatic conditions to Ningbo) the most optimal EPS thickness varied between 14 mm and 19 mm depending on the orientation of the façade. Shen (2017) discussed that above 40 mm of insulation thickness the energy savings reduce substantially and He et al. (2021b) suggested the addition of 30 mm of EPS as the viable retrofit option for 20%, 30%, and 40% energy savings targets.

In this research different insulation thickness was evaluated from 5 mm up to 50 mm to determine the most economically and environmentally appropriate option. Based on the results of previous research, it was decided to not evaluate options with more than 50 mm of insulation; in addition to that adding more insulation to the external walls may lead to problems in land ownership or other legal difficulties. The market price of the material used for the retrofit cost evaluation was 600 RMB/m^3 and for the installation, it was 28 RMB/m^2 (Liu et al., 2020b, He et al., 2021b). GHG associated with the production of EPS were 5.64 kgCO_{2eq}/kg (Liu et al., 2020b). The average lifespan of building insulation retrofit was 30 years (He et al., 2021b).

7.2.1.2 Internal walls

Since the part-time part-space heating and cooling habits create different temperature profiles within the building and even within one apartment, energy transfer between rooms was highly likely to happen. As was observed from the national and local building energy standards, the requirements for thermal transmittance of the internal walls were much less strict than those for the external walls. Therefore, it was hypothesised that adding more insulation to the internal walls might have potentially led to energy savings.

Similarly to the external walls retrofit options, the EPS insulation thickness of 5 mm and up to 50 mm was evaluated for the internal walls. However, because the addition of insulation on the internal walls would result in the reduction of total habitable and usable indoor space, options beyond 30 mm were not recommended as a retrofit option for the reasoning of potentially dissatisfied with the final results occupants. Nonetheless, if these options showed environmentally and economically effective results, they could be suggested for the design and construction stages of a building life cycle. The market price of the material used for the retrofit cost evaluation was the same as for the external walls 600 RMB/m^3 and for the installation, it was 28 RMB/m^2; GHG emissions used in the calculations were 5.64 kgCO$_{2eq}$/kg (He et al., 2021b, Liu et al., 2020b) and life expectancy was 30 years (He et al., 2021b).

7.2.1.3 Roof

For the insulation of the roof, the same material was used with thickness variations between 5 mm to 50 mm. The material and installation costs were assumed to be the same as for the walls (600 RMB/m^3 and 28 RMB/m^2 respectfully) with 30 years lifespan and the GWP were 5.64 kgCO$_{2eq}$/kg (He et al., 2021b, Liu et al., 2020b). Since for the block buildings (LR, MR, and both of the HR types) the ratio of the roof area to the external wall area was small, the energy savings coming from insulating the roof were expected to be smaller than from insulating the walls. In addition to that, the majority of these energy savings as well as the possible improvement of indoor thermal conditions would be mainly observed on the top floors.

7.2.1.4 Ground floor and internal floors/ceilings

The main reasoning behind the evaluation of additional insulation on the internal floors in contrast to insulating only the ground floor was the same as for the internal walls. Different temperature profiles created within a building by the occupants might lead to energy transfer between the floors through the thermal bridges. Thus, different insulation thickness from 5 mm to 50 mm was simulated for all building forms and construction years. EPS material costs used were 600 RMB/m^3, installation costs 28 RMB/m^2, associated CO_2 emissions were 5.64 kgCO_{2eq}/kg and lifespan was 30 years (He et al., 2021b, Liu et al., 2020b).

7.2.1.5 Windows

The replacement of old windows with the new ones that have lower thermal transmittance, Low-E coating, and smaller infiltration could prove as a viable economically and sustainably option for residential building retrofit. The energy savings coming from such a substitute could potentially depend on the window-to-wall ratio, the performance of already installed windows, the type of new windows or other parameters. In this research, a single glazed Low-E window with the aluminium frame as well as a double-glazed Low-E window with an aluminium frame were simulated. The thickness of the glass was set as 5 mm and the aluminium frame U-value was 2.775 W/m^{2}K (Van Den Bossche et al., 2015). The price for those replacements was 422.4 RMB/m^2 and 723.2 RMB/m^2 accordingly with the installation included in the price (He et al., 2021a). The GHG emissions associated with the glazing production were 20.6 kgCO_{2eq}/m^2 for Low-E single glazed glass and 52.09 kgCO_{2eq}/m^2 for Low-E double-glazed glass (O'Neill et al., 2021). As for the aluminium window frames, for the material extraction and frames manufacturing the total GHG emissions were 486 kgCO_{2eq}, however, this amount can be reduced by nearly 90% if recycled aluminium was used (Salazar, 2014, Sinha and Kutnar, 2012). Nonetheless, this research assumed the worst case scenario. The expected service life was assumed to be 25 years (He et al., 2021b).

7.2.1.6 Airtightness

The increase of building airtightness is one of the essential steps for achieving energy-efficient buildings (Burton, 2012, Parker, 2010, Riley, 2011, Shah, 2012). It can decrease both cooling and heating requirements in any type of buildings. However, in residential buildings with no auxiliary fresh air supply system the improvement of infiltration can result in CO_2 gas (as well as other contaminants) built up in the rooms causing SBS and/or BRI (Jafari et al., 2015, Mendes and Teixeira, 2014, EPA, 1991). The national and local design standards for energy efficiency in buildings require the minimum infiltration in non-ventilated buildings to be at least 1 ach (Ministry of Construction of PRC, 2001, Ministry of Construction of PRC, 2003, Ministry of Construction of PRC, 2010). Thus, improving the airtightness would require installation of an additional fresh air supply system, which, in a building that was not designed nor prepared for it, would require a considerable amount of initial investment. For this reasoning, the improvement of airtightness was not considered as an economically viable option for Ningbo residential buildings retrofit.

7.2.2 DHW upgrade

Based on the simulation results the DHW energy consumption accounted for 20%-30% of the total energy consumption in a building. Thus, improving DHW system efficiency could result in an overall decrease in residential buildings' energy demand. The upgrade proposed in this research was the installation of the gas boiler with an efficiency of 93% that according to Chinese online shopping websites could cost around 3000 RMB with installation cost usually included (excluding any additional equipment in some cases). Carbon dioxide emissions associated with the materials needed for a domestic gas boiler manufacture as well as the production of the boiler were in total 55.733 kg (Raluy and Dias, 2020). The assumed lifespan was 15 years (Raluy and Dias, 2020).

7.2.3 Heating and cooling system upgrade

Heating and cooling demands were the main contributors to the final energy consumption in studied residential buildings. Based on the simulation results together they accounted for more than 50% of the total energy demand. As the overall living conditions of the residents improve, they were predicted to develop higher expectations of the indoor thermal conditions and as a result rely even more on heating and cooling (Wang et al., 2015b, Yu et al., 2009a). This tendency could already be observed in the younger generation of occupants (Wang et al., 2015b). Therefore, it is imperative to install heating and cooling systems with higher efficiency for promoting a sustainable building environment. The newest AC units available on the market provide First Grade efficiency of COP higher than 3.4 at a cost of around 3200 RMB (based on Chinese online shopping websites) with installation costs included. According to Ren and Zhao (2014), the GHG emissions generated during the material extraction and manufacturing of a split air conditioner were 820 $kgCO_{2eq}$ and according to He et al. (2021b) the expected service life was 15 years.

7.2.4 Lighting upgrade

The 2015 DB33/1015-2015 Design standard for energy efficiency of residential buildings energy standard suggested the installation of more energy-efficient types of lighting equipment such as LED lights (Ministry of Construction of Zhejiang, 2015). According to the standard, these lamps must be at least 50% more efficient than the currently used ones. Based on that, to simulate the retrofit option of LED lights installation the average internal load created by lights had been changed to 3 W/m^2. The assumed radiant heat fraction was 0.35 (Zhong, 2016). The average cost of lights was 30.5 RMB and the GHG emissions were 12.5 $kgCO_{2eq}$ (Liu et al., 2017). Additionally, assuming that the lights were used for 6 hours a day (from 5 pm to 11 pm) every day and the lifetime of LED was 25000 hours, the service life of LED lighting upgrade was considered to be 10 years (Hicks et al., 2015).

7.2.5 Shading

The introduction of shading devices to the building can be challenging since blocking the direct sunlight would decrease the summer cooling energy demand while simultaneously increasing the winter heating requirements as well as potentially increasing whole year-round lighting energy consumption. Balancing these factors can be done by implementing shading on different facades of the buildings or with different shades.

According to Carletti et al. (2014), one of the most efficient shading devices to decrease the cooling demand in buildings was overhangs, since they block the direct sunlight before it enters the indoors and warms up the objects or air. For the HSCW climate in China, He et al. (2021a) and He et al. (2021b) suggested the introduction of a 270 mm overhang on the west façade as a suitable residential building retrofit option for energy conservation purposes. The overall cost of external overhang shading with installation was 466 RMB/m^2, lifespan assumed as 20 years, and the GHG emissions were 290 $kgCO_{2eq}/m^2$ for 300 mm overhang (Panteli et al., 2018, He et al., 2021b). In this research, two types of overhangs were evaluated: 250 mm and 300 mm on the west and south façade separately.

7.2.6 On-site renewable energy sources

The on-site renewable energy generation could be performed with many different options. Two of the simplest in installation and integration into the building were solar thermal collectors and PV panels. Since both of these options require solar radiation as the main source of energy and Ningbo is located in the southern part of China (meaning it receives a sufficient amount of annual solar radiation), both of these options could be economically and environmentally viable.

The most common way to integrate solar thermal collectors and PV panels into the building was to install them on the roof, which meant that they could compete with each other for the roof space. On the buildings where the ratio of the roof area to the total floor area of the building was big (e.g. Villa, Terraced, LR), there could potentially be enough space for both SHW and electricity production in a cost-effective and user satisfying way. However, the other buildings could present a dilemma of balancing between solar thermal collectors and PV panels. In addition to that, the delivery of generated SHW to all of the apartments in MR and HR buildings would result in high delivery thermal losses due to long distances. At the same time, supplying only the top floors with generated SHW could result in discrepancies between the residents and overall lower satisfaction with the proposed solar thermal collectors' installation. Based on that, it was decided to consider only PV panels' installation for MR, HRT and HRP. As for the other building typologies, different amounts of solar thermal collectors and PV panels were evaluated.

The average cost of an evacuated tube solar collector with 200 l storage was 5700 RMB with installation included (He et al., 2021b). The GHG emissions generated by the evacuated collector production was calculated by Beccali et al. (2016) to be 86.97 $kgCO_{2eq}/m^2$ and its lifespan 25 years. As for the polycrystalline PV panels, according to Qiu et al. (2021), a 5 kW installation cost 25,000 RMB, the GHG emissions associated with their production was calculated by Soares et al. (2018) to be 184 $kgCO_{2eq}/m^2$ and the expected service life was 25 years (Majewski et al., 2021). The PV panels installation subsidies provided by the local and national governments discussed in Chapter 4 were not considered in this research.

7.2.7 Retrofit measures summary

A summary of all of the proposed residential buildings retrofit measures was presented in Table 7.1. Each of the individual retrofit measures was attributed to either building energy reduction purposes or energy production purposes. In the energy reduction category, active systems had three specific retrofit measures concerning heating and cooling systems, DHW system and lighting. The passive systems group presented seven main specific retrofit measures improving the overall building envelope; each of the building envelope insulation measures also had ten options depending on the insulation thickness, the window replacement had two options and shading presented four options. Finally, the energy production category had either two proposed retrofit measures (PV panels and SHW collectors) or one measure (PV panels) depending on the building typology.

Energy reduction	Passive systems	External walls	Addition of 5-50 mm EPS insulation
		Internal walls	Addition of 5-30 mm EPS insulation
		Roof	Addition of 5-50 mm EPS insulation
		Ground floor	Addition of 5-50 mm EPS insulation
		Internal floors/ceilings	Addition of 5-50 mm EPS insulation
		Windows	Windows replacement with Low-E single glaze or Low-E double glaze
		Shading	250 mm and 300 mm long external overhangs on the west and/or south facade
	Active systems	DHW	Replacement of old boiler with energy-efficient gas boiler
		Heating system Cooling system	Replacement of old split air conditioning with an energy-efficient one
		Lights	Replacement of lights with LED lights
Energy production	Renewable energy	SHW	Installation of evacuated solar tube collectors
		PV panels	Installation of polycrystalline PV panels

Table 7.1 Summary of retrofit measures proposed for evaluation

Each of these twelve specific building retrofit measures was simulated individually on fifteen of the created residential building typologies using IES-VE software to evaluate the buildings' energy performance after the implementation of proposed retrofit measures. These results were further compared to the energy requirements of the baseline buildings with no retrofit intervention to determine $S_{\Delta E}$, $\Delta E_{\%}$, PBP, and ΔGWP^{r} during the service life for each of the retrofit measures.

7.3 Individual retrofit measures evaluation results and discussion

The simulation and Economic-Environment evaluation results of the individual retrofit measures on six building forms with the different year of construction can be observed in Tables 7.2-7.16. The results for each building typology included the appropriate retrofit action (if the estimated PBP was less than expected service life), the total energy consumption of the building (with that retrofit measure implemented), the energy difference between the retrofitted building and the baseline building, annual cost savings (based on annual energy savings), initial investment cost, payback period, amount of GHG emissions saved (calculated as a difference between the retrofit measure embodied GHG and the annual CO_{2eq} reductions driven by energy consumption decrease), and the estimated EE Score.

From these tables, it could be seen that the energy, cost and CO_{2eq} emissions reductions varied not only for different individual retrofit measures but also for different building typologies. At the same time, some of the proposed retrofit measures were not economically viable for all of the building typologies. For example, the replacement of windows with Low-E single or double glazing was calculated to have a PBP of over a hundred years due to high installation costs and low associated energy reductions. In addition to that, single glaze windows manufacturing produced more GHG emissions than could potentially be saved during the windows lifetime based on the simulation results. The introduction of overhang shading increased the winter heating energy consumption more than it decreased the summer cooling energy demand in some cases, while in others only slightly decreasing the overall energy demand, which was not enough to produce financial savings that could repay the initial investment. The installation of a new gas-fired hot water boiler also presented the PBP slightly greater than the boiler expected service life. Thus, these retrofit measures were not recommended for any of the building typologies.

Among the proposed appropriate retrofit actions, the ones that were economically and environmentally beneficial for all building typologies were the replacement of AC units, replacement of lights with LED light bulbs and installation of renewable energy sources. The best retrofit measure out of these based on the EE Score was the installation of energy-efficient split air conditioning units. While it was the most expensive retrofit option considering the IIC, it also provided the greatest building energy demand reduction varying from 15% up to 30% of the baseline depending on the building form and year of construction. The second best retrofit measure for the majority of building typologies considering the EE Score was light bulb replacement with LED lights. This retrofit measure was the cheapest among all of the options, while still providing a 4-8% of total energy consumption decrease. Another advantageous factor for these two retrofit measures was that they could be done and benefited from by one individual's initiative. In addition to that, they could be implemented on a single room or single piece of equipment basis, providing the residents with an opportunity to decrease the IIC and gradually retrofit their living spaces.

Evaluation of different amounts of SHW collectors' installation on the roofs of the residential buildings proved that the integration of one average-sized evacuated solar tube collector per household was the optimal solution. Installation of the second SHW collector per household increased the overall system's PBP beyond its expected service life. This was due to the fact that the hot water was generated and supplied by this system at a different time of the day than the expected demand. Unlike the SHW retrofit measure, the economic evaluation of PV panels' installation was not affected by the number of panels installed, since the excess electricity was assumed to be supplied to the grid. Based on that, it was decided to provide one household with 5 PV panels (if the roof space allowed) to maintain this retrofit measure's IIC on approximately the same level as the SHW retrofit's. However, if the financial situation and the roof space allows, this amount could be increased for greater economic and environmental benefits. Though, for MR, HRT and HRP building forms the available roof area was not enough to accommodate 5 PV panels per household, therefore, the maximum possible amount was calculated (with half of the panels' area in between the panels for easy maintenance access).

Comparing the on-site renewable energy production retrofit measures with each other the results show, that PV panels’ installation and SHW collectors’ installation performed approximately equally for Villa and Terraced building forms considering their EE Score. While SHW collectors had slightly lower IIC, PV panels provided higher $S_{\Delta E}$ and greater CO_{2eq} reductions during their service life. For LR buildings, however, PV panels’ EE Score was higher than the SHW’s score (e.g. 0.4017 and 0.3082 respectively for LR constructed before 2002). Thus, while both options presented economic and environmental benefits, PV panels’ installation was ranked higher and had a slightly higher retrofit priority.

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^r, $kgCO_{2eq}$	EE Score
Villa Before 2002	No actions taken (baseline)	15.807	NA	NA	NA	NA	NA	NA
External wall	No intervention	15.807	NA	NA	NA	NA	NA	NA
Roof	No intervention	15.807	NA	NA	NA	NA	NA	NA
First floor	No intervention	15.807	NA	NA	NA	NA	NA	NA
Internal walls	No intervention	15.807	NA	NA	NA	NA	NA	NA
Internal floors	No intervention	15.807	NA	NA	NA	NA	NA	NA
Windows	No intervention	15.807	NA	NA	NA	NA	NA	NA
Shading	No intervention	15.807	NA	NA	NA	NA	NA	NA
Boiler	No intervention	15.807	NA	NA	NA	NA	NA	NA
AC	AC replacement	11.782	25.5%	2165.72	12800	5.9	-57706.3	0.6276
Lights	Lights replacement with LEDs	15.031	4.9%	417.81	884.5	2.1	-7481.2	0.5030
SHW	1 Evacuated tube solar collector	14.754	6.7%	566.57	5700	10.1	-26216.8	0.2575
PV panels	5 polycrystalline PV panels	14.670*	7.2%*	611.98	6250	10.2	-27231.5	0.2640

Table 7.2 Results of individual building retrofits simulation for Villa Before 2002 (ΔGWP^r calculated based on RM's service life)
**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^{r}, $kgCO_{2eq}$	EE Score
Villa 2002-2010	No actions taken (baseline)	15.3887	NA	NA	NA	NA	NA	NA
External wall	No intervention	15.3887	NA	NA	NA	NA	NA	NA
Roof	No intervention	15.3887	NA	NA	NA	NA	NA	NA
First floor	No intervention	15.3887	NA	NA	NA	NA	NA	NA
Internal walls	No intervention	15.3887	NA	NA	NA	NA	NA	NA
Internal floors	No intervention	15.3887	NA	NA	NA	NA	NA	NA
Windows	No intervention	15.3887	NA	NA	NA	NA	NA	NA
Shading	No intervention	15.3887	NA	NA	NA	NA	NA	NA
Boiler	No intervention	15.3887	NA	NA	NA	NA	NA	NA
AC	AC replacement	11.5862	24.7%	2045.75	12800	6.3	-54327.9	0.6276
Lights	Lights replacement with LEDs	14.6660	4.7%	388.97	884.5	2.3	-6939.8	0.5015
SHW	1 Evacuated tube solar collector	14.3360	6.8%	566.57	5700	10.1	-26216.8	0.2686
PV panels	5 polycrystalline PV panels	14.2512*	7.4%*	611.96	6250	10.2	-27231.48	0.2765

Table 7.3 Results of individual building retrofits simulation for Villa 2002-2010 (ΔGWP^{r} calculated based on RM's service life)

**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^{r}, $kgCO_{2eq}$	EE Score
Villa 2011-2015	No actions taken (baseline)	14.9654	NA	NA	NA	NA	NA	NA
External wall	No intervention	14.9654	NA	NA	NA	NA	NA	NA
Roof	No intervention	14.9654	NA	NA	NA	NA	NA	NA
First floor	No intervention	14.9654	NA	NA	NA	NA	NA	NA
Internal walls	No intervention	14.9654	NA	NA	NA	NA	NA	NA
Internal floors	No intervention	14.9654	NA	NA	NA	NA	NA	NA
Windows	No intervention	14.9654	NA	NA	NA	NA	NA	NA
Shading	No intervention	14.9654	NA	NA	NA	NA	NA	NA
Boiler	No intervention	14.9654	NA	NA	NA	NA	NA	NA
AC	AC replacement	11.3520	24.1%	1944.01	12800	6.6	-51463.0	0.6276
Lights	Lights replacement with LEDs	14.2367	4.9%	392.04	884.5	2.3	-6997.4	0.5079
SHW	1 Evacuated tube solar collector	13.9123	7.0%	566.57	5700	10.1	-26216.8	0.2805
PV panels	5 polycrystalline PV panels	13.8279*	7.6%*	611.96	6250	10.2	-27231.5	0.2883

Table 7.4 Results of individual building retrofits simulation for Villa 2011-2015 (ΔGWP^{r} calculated based on RM's service life)
**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^{r}, $kgCO_{2eq}$	EE Score
Terraced Before 2002	No actions taken (baseline)	49.7081	NA	NA	NA	NA	NA	NA
External wall	No intervention	49.7081	NA	NA	NA	NA	NA	NA
Roof	No intervention	49.7081	NA	NA	NA	NA	NA	NA
First floor	No intervention	49.7081	NA	NA	NA	NA	NA	NA
Internal walls	No intervention	49.7081	NA	NA	NA	NA	NA	NA
Internal floors	No intervention	49.7081	NA	NA	NA	NA	NA	NA
Windows	No intervention	49.7081	NA	NA	NA	NA	NA	NA
Shading	No intervention	49.7081	NA	NA	NA	NA	NA	NA
Boiler	No intervention	49.7081	NA	NA	NA	NA	NA	NA
AC	AC replacement	41.2146	17.1%	4569.50	48000	10.5	-116376.5	0.6040
Lights	Lights replacement with LEDs	46.0271	7.4%	1980.38	3965	2.0	-35553.1	0.6256
SHW	5 Evacuated tube solar collector	45.1654	9.4%	2519.67	28500	11.3	-116386.0	0.4472
PV panels	25 polycrystalline PV panels	44.1613*	11.4%*	3059.88	31250	10.2	-136157.4	0.5186

Table 7.5 Results of individual building retrofits simulation for Terraced Before 2002 (ΔGWP^{r} calculated based on RM's service life)
**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^{r}, $kgCO_{2eq}$	EE Score
Terraced 2002-2010	No actions taken (baseline)	48.5877	NA	NA	NA	NA	NA	NA
External wall	No intervention	48.5877	NA	NA	NA	NA	NA	NA
Roof	No intervention	48.5877	NA	NA	NA	NA	NA	NA
First floor	No intervention	48.5877	NA	NA	NA	NA	NA	NA
Internal walls	No intervention	48.5877	NA	NA	NA	NA	NA	NA
Internal floors	No intervention	48.5877	NA	NA	NA	NA	NA	NA
Windows	No intervention	48.5877	NA	NA	NA	NA	NA	NA
Shading	No intervention	48.5877	NA	NA	NA	NA	NA	NA
Boiler	No intervention	48.5877	NA	NA	NA	NA	NA	NA
AC	AC replacement	40.6700	16.3%	4259.70	48000	11.3	-107653.2	0.5912
Lights	Lights replacement with LEDs	44.8511	7.7%	2010.29	3965	2.0	-36114.7	0.6418
SHW	5 Evacuated tube solar collector	43.9043	9.6%	2519.67	28500	11.3	-116386.0	0.4632
PV panels	25 polycrystalline PV panels	42.9002*	11.7%*	3059.88	31250	10.2	-136157.4	0.5381

Table 7.6 Results of individual building retrofits simulation for Terraced 2002-2010 (ΔGWP^{r} calculated based on RM's service life)

**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^{r}, $kgCO_{2eq}$	EE Score
Terraced 2011-2015	No actions taken (baseline)	47.0600	NA	NA	NA	NA	NA	NA
External wall	No intervention	47.0600	NA	NA	NA	NA	NA	NA
Roof	No intervention	47.0600	NA	NA	NA	NA	NA	NA
First floor	No intervention	47.0600	NA	NA	NA	NA	NA	NA
Internal walls	No intervention	47.0600	NA	NA	NA	NA	NA	NA
Internal floors	No intervention	47.0600	NA	NA	NA	NA	NA	NA
Windows	No intervention	47.0600	NA	NA	NA	NA	NA	NA
Shading	No intervention	47.0600	NA	NA	NA	NA	NA	NA
Boiler	No intervention	47.0600	NA	NA	NA	NA	NA	NA
AC	AC replacement	39.8366	15.3%	3886.19	48000	12.4	-97134.5	0.5757
Lights	Lights replacement with LEDs	43.3040	8.0%	2020.73	3965	2.0	-36310.6	0.6613
SHW	5 Evacuated tube solar collector	42.3766	10.0%	2519.67	28500	11.3	-116386.0	0.4860
PV panels	25 polycrystalline PV panels	41.3725*	12.1%*	3059.88	31250	10.2	-136157.4	0.5657

Table 7.7 Results of individual building retrofits simulation for Terraced 2011-2015 (ΔGWP^{r} calculated based on RM's service life)
**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^{r}, $kgCO_{2eq}$	EE Score
LR Before 2002	No actions taken (baseline)	186.070	NA	NA	NA	NA	NA	NA
External wall	40 mm EPS insulation added	182.190	2.1%	2088.8	82576	39.5	-106892	0.1020
Roof	45 mm EPS insulation added	185.097	0.5%	523.7	24239	46.3	-26141	0.1396
First floor	40 mm EPS insulation added	184.893	0.6%	633.6	22917	36.2	-32701	0.1505
Internal walls	30 mm EPS insulation added	182.520	1.9%	1910.1	86020	45.0	-98082	0.0951
Internal floors	35 mm EPS insulation added	179.632	3.5%	3464.1	151162	43.6	-176829	0.1288
Windows	No intervention	186.070	NA	NA	NA	NA	NA	NA
Shading	No intervention	186.070	NA	NA	NA	NA	NA	NA
Boiler	No intervention	186.070	NA	NA	NA	NA	NA	NA
AC	AC replacement	139.357	25.1%	25131.9	201600	8.0	-656051	0.6148
Lights	Lights replacement with LEDs	177.370	4.7%	4680.8	7473	1.6	-84810	0.5004
SHW	21 Evacuated tube solar collector	168.504	9.4%	9450.9	119700	11.3	-435708	0.3082
PV panels	105 polycrystalline PV panels	162.183*	12.8%*	12851.5	131250	10.2	-571860	0.4017

Table 7.8 Results of individual building retrofits simulation for LR Before 2002 (ΔGWP^{r} calculated based on RM’s service life)
**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^{r}, $kgCO_{2eq}$	EE Score
LR 2002-2010	No actions taken (baseline)	182.816	NA	NA	NA	NA	NA	NA
External wall	40 mm EPS insulation added	179.390	1.9%	1843.3	82576	44.8	-93069	0.0959
Roof	No intervention	182.816	NA	NA	NA	NA	NA	NA
First floor	40 mm EPS insulation added	181.91	0.5%	487.3	22917	47	-24463	0.1462
Internal walls	No intervention	182.816	NA	NA	NA	NA	NA	NA
Internal floors	35 mm EPS insulation added	176.873	3.3%	3197.2	151162	47.3	-161798	0.1234
Windows	No intervention	182.816	NA	NA	NA	NA	NA	NA
Shading	No intervention	182.816	NA	NA	NA	NA	NA	NA
Boiler	No intervention	182.816	NA	NA	NA	NA	NA	NA
AC	AC replacement	137.573	24.7%	24340.4	201600	8.3	-633762	0.6148
Lights	Lights replacement with LEDs	173.927	4.9%	4782.1	7473	1.6	-86712	0.5060
SHW	21 Evacuated tube solar collector	165.249	9.6%	9450.9	119700	11.3	-435708	0.3178
PV panels	105 polycrystalline PV panels	158.928*	13.1%*	12851.5	131250	10.2	-571860	0.4144

Table 7.9 Results of individual building retrofits simulation for LR 2002-2010 (ΔGWP^{r} calculated based on RM's service life)
**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^r, $kgCO_{2eq}$	EE Score
LR 2011-2015	No actions taken (baseline)	180.790	NA	NA	NA	NA	NA	NA
External wall	25 mm EPS insulation added	178.214	1.4%	1385.9	68284	49.3	-71336	0.0900
Roof	No intervention	180.790	NA	NA	NA	NA	NA	NA
First floor	No intervention	180.790	NA	NA	NA	NA	NA	NA
Internal walls	No intervention	182.816	NA	NA	NA	NA	NA	NA
Internal floors	No intervention	180.790	NA	NA	NA	NA	NA	NA
Windows	No intervention	182.816	NA	NA	NA	NA	NA	NA
Shading	No intervention	182.816	NA	NA	NA	NA	NA	NA
Boiler	No intervention	182.816	NA	NA	NA	NA	NA	NA
AC	AC replacement	136.458	24.5%	23850.5	201600	8.5	-619967	0.6148
Lights	Lights replacement with LEDs	171.319	5.2%	5095.3	7473	1.5	-92593	0.5153
SHW	21 Evacuated tube solar collector	163.223	9.7%	9450.9	119700	11.3	-435708	0.3240
PV panels	105 polycrystalline PV panels	156.902*	13.2%*	12851.5	131250	10.2	-571860	0.4228

Table 7.10 Results of individual building retrofits simulation for LR 2011-2015 (ΔGWP^r calculated based on RM's service life)
**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^r, $kgCO_{2eq}$	EE Score
MR 2002-2010	No actions taken (baseline)	601.016	NA	NA	NA	NA	NA	NA
External wall	40 mm EPS insulation added	586.318	2.4%	7907.3	256204	32.4	-411991	0.1120
Roof	No intervention	601.016	NA	NA	NA	NA	NA	NA
First floor	40 mm EPS insulation added	599.973	0.2%	561.2	25211	44.9	-28327	0.3548
Internal walls	No intervention	601.016	NA	NA	NA	NA	NA	NA
Internal floors	35 mm EPS insulation added	580.475	3.4%	11051.2	451382	40.8	-567848	0.1276
Windows	No intervention	601.016	NA	NA	NA	NA	NA	NA
Shading	No intervention	601.016	NA	NA	NA	NA	NA	NA
Boiler	No intervention	601.016	NA	NA	NA	NA	NA	NA
AC	AC replacement	449.035	25.3%	81766.0	729600	8.9	-2115558	0.6121
Lights	Lights replacement with LEDs	572.851	4.7%	15152.5	22021	1.5	-275436	0.5002
SHW	No intervention	601.016	NA	NA	NA	NA	NA	NA
PV panels	180 polycrystalline PV panels	560.066*	6.8%*	22031.1	225000	10.2	-980333	0.2396

Table 7.11 Results of individual building retrofits simulation for MR 2002-2010 (ΔGWP^r calculated based on RM's service life)
**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^{r}, $kgCO_{2eq}$	EE Score
MR 2010-2015	No actions taken (baseline)	595.286	NA	NA	NA	NA	NA	NA
External wall	No intervention	595.286	NA	NA	NA	NA	NA	NA
Roof	No intervention	595.286	NA	NA	NA	NA	NA	NA
First floor	25 mm EPS insulation added	594.469	0.1%	439.4	20848	47.4	-22698	0.4044
Internal walls	No intervention	595.286	NA	NA	NA	NA	NA	NA
Internal floors	25 mm EPS insulation added	578.200	2.9%	9192.1	396111	43.1	-478730	0.1127
Windows	No intervention	595.286	NA	NA	NA	NA	NA	NA
Shading	No intervention	595.286	NA	NA	NA	NA	NA	NA
Boiler	No intervention	595.286	NA	NA	NA	NA	NA	NA
AC	AC replacement	445.648	25.1%	80516.1	729600	9.1	-2080362	0.6114
Lights	Lights replacement with LEDs	566.612	4.8%	15437.5	22021	1.4	-280786	0.4824
SHW	No intervention	595.286	NA	NA	NA	NA	NA	NA
PV panels	180 polycrystalline PV panels	554.336*	6.9%*	22031.1	225000	10.2	-980333	0.2408

Table 7.12 Results of individual building retrofits simulation for MR 2011-2015 (ΔGWP^{r} calculated based on RM's service life)
**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^{r}, $kgCO_{2eq}$	EE Score
HRT 2002-2010	No actions taken (baseline)	804.377	NA	NA	NA	NA	NA	NA
External wall	35 mm EPS insulation added	790.343	1.7%	7550.5	315903	41.8	-387060	0.0831
Roof	No intervention	804.377	NA	NA	NA	NA	NA	NA
First floor	No intervention	804.377	NA	NA	NA	NA	NA	NA
Internal walls	No intervention	804.377	NA	NA	NA	NA	NA	NA
Internal floors	40 mm EPS insulation added	774.2317	3.7%	16218.3	717756	44.3	-819993	0.1145
Windows	No intervention	804.377	NA	NA	NA	NA	NA	NA
Shading	No intervention	804.377	NA	NA	NA	NA	NA	NA
Boiler	No intervention	804.377	NA	NA	NA	NA	NA	NA
AC	AC replacement	564.134	29.9%	129251.0	864000	6.7	-3418289	0.6136
Lights	Lights replacement with LEDs	767.573	4.6%	19800.6	29280	1.5	-359721	0.4823
SHW	No intervention	804.377	NA	NA	NA	NA	NA	NA
PV panels	180 polycrystalline PV panels	767.977*	4.5%*	19583.2	200000	10.2	-871407	0.1702

Table 7.13 Results of individual building retrofits simulation for HRT 2002-2010 (ΔGWP^{r} calculated based on RM's service life)
**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^r, $kgCO_{2eq}$	EE Score
HRT 2011-2015	No actions taken (baseline)	798.503	NA	NA	NA	NA	NA	NA
External wall	25 mm EPS insulation added	787.187	1.4%	6088.2	277221	45.5	-315613	0.0798
Roof	No intervention	798.503	NA	NA	NA	NA	NA	NA
First floor	No intervention	798.503	NA	NA	NA	NA	NA	NA
Internal walls	No intervention	798.503	NA	NA	NA	NA	NA	NA
Internal floors	25 mm EPS insulation added	775.7432	2.9%	12244.8	593529	48.5	-631235	0.0951
Windows	No intervention	798.503	NA	NA	NA	NA	NA	NA
Shading	No intervention	798.503	NA	NA	NA	NA	NA	NA
Boiler	No intervention	798.503	NA	NA	NA	NA	NA	NA
AC	AC replacement	559.967	29.9%	128332.3	864000	6.7	-3392417	0.6136
Lights	Lights replacement with LEDs	760.572	4.8%	20406.8	29280	1.4	-371101	0.4855
SHW	No intervention	798.503	NA	NA	NA	NA	NA	NA
PV panels	180 polycrystalline PV panels	762.103*	4.6%*	19583.2	200000	10.2	-871407	0.1710

Table 7.14 Results of individual building retrofits simulation for HRT 2011-2015 (ΔGWP^r calculated based on RM's service life)

**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^{r}, $kgCO_{2eq}$	EE Score
HRP 2002-2010	No actions taken (baseline)	1607.38	NA	NA	NA	NA	NA	NA
External wall	40 mm EPS insulation added	1584.78	1.4%	12161.6	471172	38.7	-623613	0.0797
Roof	No intervention	1607.38	NA	NA	NA	NA	NA	NA
First floor	40 mm EPS insulation added	1605.74	0.1%	885.3	44090	49.8	-44120	0.4030
Internal walls	No intervention	1607.38	NA	NA	NA	NA	NA	NA
Internal floors	No intervention	1607.38	NA	NA	NA	NA	NA	NA
Windows	No intervention	1607.38	NA	NA	NA	NA	NA	NA
Shading	No intervention	1607.38	NA	NA	NA	NA	NA	NA
Boiler	No intervention	1607.38	NA	NA	NA	NA	NA	NA
AC	AC replacement	1184.45	26.3%	227538.7	1728000	7.6	-5964656	0.6102
Lights	Lights replacement with LEDs	1530.83	4.8%	41183.7	58560	1.4	-749151	0.3987
SHW	No intervention	1607.38	NA	NA	NA	NA	NA	NA
PV panels	180 polycrystalline PV panels	1534.58*	4.5%*	39166.4	400000	10.2	-883774	0.1426

Table 7.15 Results of individual building retrofits simulation for HRP 2002-2010 (ΔGWP^{r} calculated based on RM's service life)

**On-site energy production is assumed as energy reduction*

	Appropriate action	E_{total}, MWh	$\Delta E^{\%}$, %	$S_{\Delta E}$, RMB	IIC, RMB	PBP, years	ΔGWP^r, $kgCO_{2eq}$	EE Score
HRP 2011-2015	No actions taken (baseline)	1605.02	NA	NA	NA	NA	NA	NA
External wall	25 mm EPS insulation added	1587.09	1.1%	9646.7	389623	40.4	-504969	0.0714
Roof	No intervention	1605.02	NA	NA	NA	NA	NA	NA
First floor	20 mm EPS insulation added	1603.28	0.1%	968.7	36459	36.2	-49962	0.4034
Internal walls	No intervention	1605.02	NA	NA	NA	NA	NA	NA
Internal floors	No intervention	1605.02	NA	NA	NA	NA	NA	NA
Windows	No intervention	1605.02	NA	NA	NA	NA	NA	NA
Shading	No intervention	1605.02	NA	NA	NA	NA	NA	NA
Boiler	No intervention	1605.02	NA	NA	NA	NA	NA	NA
AC	AC replacement	1182.82	26.3%	227141.6	1728000	7.6	-5953472	0.6084
Lights	Lights replacement with LEDs	1528.83	4.7%	40987.2	58560	1.4	-745461	0.3463
SHW	No intervention	1607.38	NA	NA	NA	NA	NA	NA
PV panels	180 polycrystalline PV panels	1532.22*	4.5%*	39166.4	400000	10.2	-883774	0.1351

Table 7.16 Results of individual building retrofits simulation for HRP 2011-2015 (ΔGWP^r calculated based on RM's service life)
**On-site energy production is assumed as energy reduction*

As it was discussed in Chapter 6, Villa and Terraced building forms had a greater floor area per occupant resulting in lower average building EUI and a large amount of unoccupied and non-conditioned spaces. In addition to that, they had the biggest C_f with big outside wall areas. This resulted in high IIC to retrofit all of the walls and low energy decrease since in some of the continuously unoccupied rooms the temperatures were similar to the ones outside, therefore little energy transfer was occurring between them and outdoors. All of these factors contributed to the fact that building envelope retrofit options proved to be not economically viable for Villa and Terraced building typologies with retrofit measures' PBP greater than 50 years. Nevertheless, energy decreases of up to 10% were achieved with some of the building envelope retrofit measures such as adding insulation to the internal walls or internal floors/ceilings. Considering the fact that nearly 50% of the final IIC of adding 50 mm of EPS insulation to the walls was driven by the retrofit labour cost, it could be said that while additional insulation did not prove to be an attractive retrofit investment, it could, however, be a valid point of consideration during the building design and construction phases.

Nonetheless, both Villa and Terraced building forms proved to benefit most from the replacement of old AC units with new energy-efficient ones. Villa building form, having four units per household, showed total energy consumption decreases from 24.1% up to 25.5% depending on the year of construction. Terraced houses with three AC units per household and relatively similar occupancy density as Villas were observed to have smaller energy consumption decrease after the AC units replacement of 15.3%-17.1%. For both of these building forms the second-best option considering the EE Score was lights replacement (4.7%-4.9% of $\Delta E^{\%}$ for Villa and 7.4%-8% reduction for Terraced), followed by the PV panels installation (7.2%-7.6% decrease in Villas and 11.4%-12.1% in Terraced) and SHW collectors installation (6.7%-7% reduction in Villas and 9.4%-10% of total building energy decrease for Terraced houses).

Similarly to the Villas and Terraced houses, L building typologies benefited most from the same retrofit measures being AC units replacement, LED lights installation, and PV panels and SHW collectors integration into the building. Unlike for Villas and Terraced building forms, however, additional insulation of different thicknesses on all of the building envelope elements was recommended as viable retrofit measures for LR constructed before 2002 building typology. Newer buildings from that building form were observed to benefit less from such interventions due to having overall higher insulation levels. Thus, for LR buildings constructed between 2002 and 2011, it was recommended to add insulation to external walls, first floor and internal floors/ceilings, while for LR buildings from the construction period of 2011-2015 the additional insulation was economically beneficial only on the external walls. Overall, the retrofit measures involving increase of insulation of the building envelope elements were determined to have a lower EE Score than the active systems and renewable energy concerning measures, but since they proved to be economically and environmentally advantageous, they were recommended for further review in combination with other proposed measures.

The first two best retrofit measures for MR buildings were the replacement of AC units with energy-efficient ones and the replacement of lights with LED bulbs. SHW collectors' installation, however, was not considered for this building form as was discussed above and the amount of roof space available was not enough to accommodate 5 PV panels per household. As the result, the total building energy consumption difference between baseline MR building and with PV panels retrofit ($\Delta E^{\%}=6.9\%$) was nearly a half of that presented by Terraced ($\Delta E^{\%}=12.1\%$) and LR buildings ($\Delta E=13.2\%$). Thus, the EE Score of PV panels installation was also decreased resulting in the ground floor insulation retrofit presenting a higher beneficial value. Among other building envelope elements retrofits, additional insulation on internal floors was recommended for MR buildings constructed during both of the evaluated periods and external wall insulation improvement were economically viable only for buildings built between 2002 and 2010.

HRP building typologies displayed similar retrofit measures evaluation results as the MR typologies with only two differences. Since the first floor area of HRP was the greatest among all of the building forms, these buildings presented very high EE Score for ground floor insulating activities making this retrofit measure second best to AC units replacement based on EE Score. They also benefited from additional external wall insulation regardless of the year of construction. On the other hand, HRT buildings' small ground floor area did not influence the overall building energy consumption results to a significant extent and, therefore, its insulation was not economically beneficial. The internal floors insulating activities, however, were recommended for these building typologies as individual measures.

The implementation of EE Score as the main index of comparison among various retrofit measures allowed for an equal evaluation of each retrofit activity based on multiple parameters important for this research. Comparing Figure 7.1 that showed $\Delta E^{\%}$ of each appropriate retrofit action for all the considered building typologies with Figure 7.2 that showed EE Score revealed that while the total energy reduction was a contributing factor to the evaluation of a retrofit measure, it was not the most influential one. For example, the installation of LED light bulbs provided relatively low ΔE especially comparing with the top four energy reducing retrofit activities. However, considering its low IIC and significant reductions of GWP during their expected service life, the average EE Score of lights replacement was second best to AC unit replacement. A similar situation could be observed for the first floor insulating measure in some of the building typologies, where even though that $\Delta E^{\%}$ was relatively low, the EE Score was comparatively high.

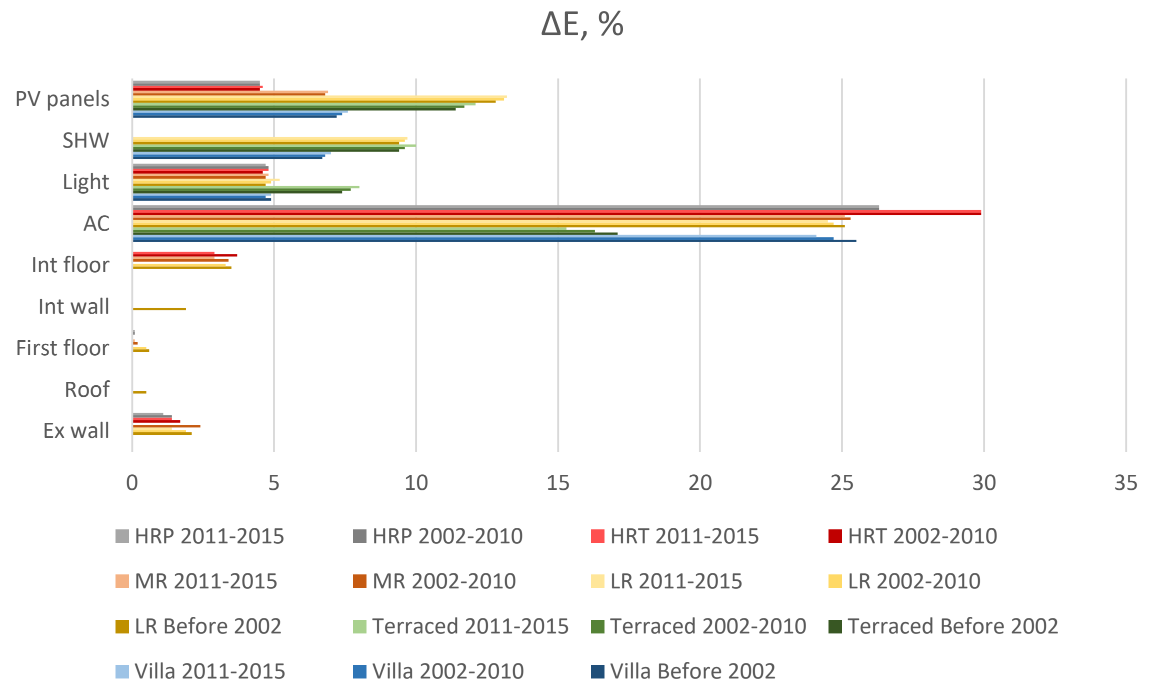


Figure 7.1 Comparison of ΔE% of each individual retrofit measure on all building typologies

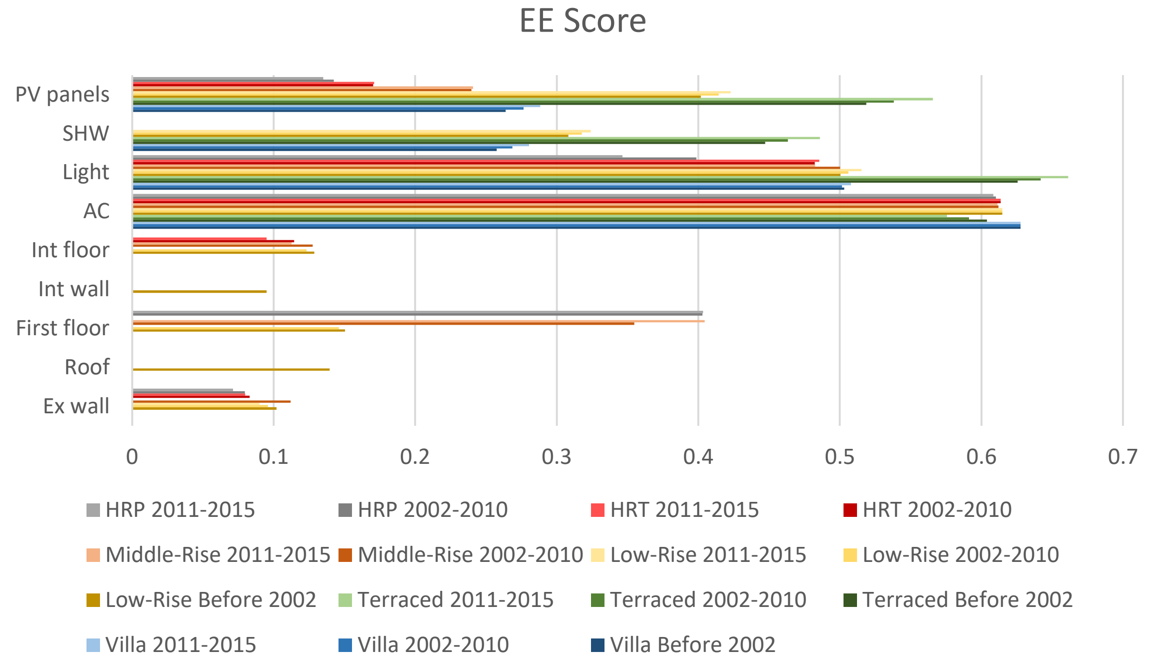


Figure 7.2 Comparison of EE Score of each individual retrofit measure on all building typologies

Based on these results, several conclusion points can be drawn. First of all, which retrofit measures were estimated to be the most economically and environmentally beneficial highly depended on the buildings’ construction forms and their year of construction. This made building typologies an essential tool for large scale residential building retrofit measures evaluation that could assist in determining the most appropriate actions and estimating the expected energy consumption reductions.

Secondly, it can be said that for the majority of building typologies the building envelope retrofit could not achieve lifetime financial savings large enough to cover the material and labour costs. This goes against some of the other research on the residential building sector in the HSCW climate zone (Ge et al., 2021, He et al., 2021a, Liu et al., 2020b, Pan et al., 2012, Yu et al., 2009b, Zhu et al., 2011, Zhang et al., 2019, Ouyang et al., 2009), where additional insulation was stated to be a viable method to increase building sustainability. These discrepancies in results were largely attributed to lack of cost evaluation, prevailing consideration of additional insulation as overall building quality improvement during the design and construction phase, or, in the research where these interventions were considered as retrofit activities, the assigned occupancy behaviour and space conditioning schedules were on the continuous (often whole-building) operation mode. Thus, the results collected in this research highlighted and emphasised the importance of evaluating the actual situation in the studied areas, integrating the local occupant behaviour patterns, and considering the total retrofit costs.

Thirdly, the residential buildings with more recent years of construction showed lower energy reductions while implementing the same retrofit measures focused on heating and cooling energy demand decreases as older buildings. As it was discussed before, newer buildings had to follow more strict building energy standards making their insulation levels and/or airtightness higher. Consequently, the same thickness of insulation material was less impactful on them. In addition to that, their overall cooling and heating energy consumption was lower, which meant that the replacement of AC units also resulted in a smaller total energy consumption difference, since overall energy demand in a building was comprised of heating, cooling, lighting, equipment, and hot water generation

Finally, for the building envelope retrofit (which included walls, roof, and floors insulation, window replacement and overhangs), a substantial amount of the total cost was derived from the installation expenses. In some situations, the equipment price was less than the required labour costs. While these expenses were a vital point of consideration for retrofit scenarios that could make a retrofit measure unaffordable, the installation costs could be eliminated or at least drastically decreased if implemented in the early stages of building design. Thus, based on these results, the addition of insulation to the building envelope elements or energy-efficient windows installation during the design and construction phase of the building lifecycle proved to be economically and environmentally viable consideration points for the building design teams. While on their own each of these measures was reducing the total building energy consumption on average by a few per cent and maximum up to ten per cent, in the course of the insulation material lifecycle and in a situation of combining insulation measures on one building these numbers would add up to substantial amounts of energy saved and carbon dioxide emissions reduced. Thus, more strict design standards for energy efficiency in the residential buildings with lower required U-values were suggested by this research as means to improve the built environment sustainability and resilience towards climate change and occupants' increasing energy demand driven by raised indoor comfort requirements.

7.4 Evaluation of retrofit packages results and discussion

7.4.1 Retrofit measures interactions

Building is a dynamic system that combines many variables determining its energy and indoor environment comfort performance. These variables interact with each other directly or indirectly influencing the overall building condition. When considering several retrofit measures, their interaction must be taken into account to understand if the proposed actions will benefit each other and increase the potential energy reductions or they will diminish each other's effects. Simulating the individual retrofit measures on residential buildings with different years of construction and different building envelope performances allowed to observe and predict the potential influence of individual retrofit measures on each other as well as the overall final performance of a retrofit package. Thus, the collected results were enough to determine how, if, and to what extent the retrofit measures were interacting.

Two of the most independent of all the other passive or active building systems were the PV panels and the evacuated tube solar collectors. These two retrofit measures generated equal amounts of electricity and hot water per installed equipment in all of the building typologies regardless of the buildings' year of construction. This was because their performance was not dependent on the indoor environment or the total energy consumption in the building, only on the outside solar conditions. The only drawback that could diminish their potency as discussed previously was the roof space, which meant that they could potentially compete for the available area. This did not happen in the observed building typologies, since for the buildings that had a low ratio of roof area to the total living floor area (MR and HR buildings), SHW was not considered. In addition to that, the PV panels had no effect on any of the other systems' performance. The installation of the SHW system, however, would have interacted with the potential savings from boiler replacement if both of these systems were to be installed in the same building. In that case, a new simulation with Economic-Environmental analysis would be performed for boiler retrofit measure to determine its PBP. But, since in this research the replacement of boiler was not recommended in the first place, such analysis was not performed.

According to the literature review (Zhong, 2016, Hicks et al., 2015, Liu et al., 2017), the lighting system in a building had an influence on the heating and cooling requirements slightly warming up the space through convection, conduction and radiation. Thus, implementing more energy-efficient light bulbs not only affected the lighting energy consumption but also increased heating and decreased cooling energy requirements. The results obtained in this research were in line with other literature's findings. On average the replacement of existing light bulbs with energy-efficient LED lights led to 2.5-3% of heating energy demand difference, considering the total buildings energy demand this variance was around 0.4%. Its effect on the cooling energy demand was much smaller. Since the heating demand increased, the potential savings coming from retrofit measures concerning the AC replacement and additional insulation would also increase. However, considering how small the difference in heating and cooling energies were compared to the change in lighting demand or overall building energy decrease caused by bulb replacement or other retrofit measures, the total influence of light replacement on other retrofit measures performance was highly likely to not be significant enough to change their PBP.

Among all of the proposed retrofit measures, the highest interaction was observed to be between AC replacement and insulating actions and among all of the building envelope insulation retrofits. As it can be seen from Tables 7.2-7.16 presenting the results of individual retrofit measures, in the newer buildings with better thermal resistance ΔE caused by AC replacement was lower than in the buildings of the same building form but an older year of construction. These variations were up to 1.7% of the total building energy consumption. Thus, better building insulation could increase PBP of AC replacement retrofit, however, because the analysed PBP of this retrofit measure was much smaller than the expected service life, the proposed insulation activities would not cause the AC replacement to become financially impractical. In addition to that, the ranking of AC replacement based on EE Score was much higher for all building typologies than the insulation activities, thus, it was more important to evaluate its effect on the building envelope retrofit measures.

The 15%-30% of total building energy demand decrease (entirely coming from heating and cooling energy decreases) driven by AC replacement would drastically influence the energy reductions caused by building envelope upgrade since lower energy demand means smaller energy savings even if the percentage ratios were the same. That would increase insulating activities' PBP, which for many of them was nearly 50 years, making these retrofit measures financially impractical and unviable. Therefore, a combinatorial energy simulation had to be made for all the building typologies where the AC replacement and additional insulation were proposed. These simulations were done in the ranked order based on the retrofit measures EE Score starting with the highest one by one. If any of them was found to have PBP more than 50 years during the initial retrofit measures combinations, the simulations with a higher number of retrofit measures including that specific measure were not suggested. Based on the proposed methodology and individual retrofit measures simulations the total number of combinatorial simulations necessary to precisely evaluate their effect on each other was maximum 43.

7.4.2 Evaluation of retrofit measures combinations

The evaluation of individual retrofit measures and their influence on each other made it clear that the assessment of combinations of retrofit actions was necessary to more precisely analyse the applicability of proposed retrofits. Thus, the initial combinations of AC replacement and single building envelope insulation retrofits were done for LR, MR, HRT and HRP building forms to determine if after replacement of the AC additional insulation would still be financially and environmentally beneficial. As discussed previously, this iteration of simulations was not executed on Villa and Terraced buildings, because it was found that additional insulation does not present a good financial investment on the baseline non-retrofitted building. Thus, totally 22 building energy simulations were performed at this stage.

	E_{total}, MWh	ΔE, %	EPS cost, RMB	$S_{\Delta E}$, RMB	PBP
LR Before 2002 New AC (baseline)	139.3569				
F_1	138.7051	0.47	31290	350.7	89.2
Roof	138.8232	0.38	32723	287.1	114.0
F_{int}	136.1665	2.29	209005	1716.4	121.8
W_{ext}	137.2067	1.54	112748	1156.8	97.5
W_{int}	137.4554	1.36	120615	1023.0	117.9
LR 2002-2010 New AC (baseline)	137.5734				
F_1	136.9887	0.43	31290	314.6	99.5
F_{int}	136.1665	1.02	209005	756.9	276.1
W_{ext}	137.2067	0.92	112748	681.5	165.4
LR 2011-2015 New AC (baseline)	136.4581				
W_{ext}	135.0289	1.05	97265	768.9	126.5
MR 2002-2010 New AC (baseline)	448.0139				
F_1	447.3691	0.14	34423	346.9	99.2
F_{int}	436.7228	2.52	624105	6074.6	102.7
W_{ext}	439.7902	1.84	349817	4424.4	79.1
MR 2011-2015 New AC (baseline)	444.6274				
F_1	443.6456	0.22	29696	528.2	56.2
F_{int}	434.4016	2.30	564228	5501.5	102.6
HRT 2002-2010 New AC (baseline)	594.0338				
F_{int}	574.6305	3.27	980013	10439.0	93.9
W_{ext}	581.9867	2.03	436784	6481.3	67.4
HRT 2011-2015 New AC (baseline)	590.0823				
F_{int}	576.7198	2.26	845434	7189.0	117.6
W_{ext}	582.9422	1.21	394879	3841.4	102.8
HRP 2002-2010 New AC (baseline)	1184.4486				
F_1	1183.5387	0.08	60201	489.5	123.0
W_{ext}	1171.9058	1.06	643331	6748.0	95.3
HRP 2011-2015 New AC (baseline)	1182.8226				
F_1	1182.2062	0.05	49178	331.6	148.3
W_{ext}	1173.2333	0.81	554986	5159.0	107.6

Table 7.17 Results of retrofit measures combinations with new AC units installed

The results of the initial combinatorial retrofit measures simulations presented in Table 7.17 showed that after the replacement of old AC units with new energy-efficient ones it was no longer economically viable to add insulation to any of the building envelope elements for all of the buildings forms. The PBP for such activities was considerably bigger than the established 50 years limit. This proves the hypothesis discussed in the previous section that the AC replacement would diminish the effectiveness of insulation retrofits. Since adding insulation to any single one of the building envelope elements was determined to be uneconomical, adding insulation to two or more building elements would also be not practical since they would further decrease the retrofits' energy reductions. This statement had to be further validated on a case scenario.

7.4.2.1 Full insulation retrofit application on LR building built before 2002

To observe if the installation of several retrofit options that were found to be economically unviable on individual level would result in a financially practical or unpractical retrofit package, all the individual insulation retrofit measures presented in Table 7.20 above were integrated into an LR building built before 2002 with new AC units installed. The results of this combinatorial retrofit simulation were outlined in Table 7.18.

	E_{total}, MWh	$\Delta E^{\%}$, %	EPS cost, RMB	$S_{\Delta E}$, RMB	PBP
LR Before 2002 New AC (baseline)	139.3569				
F_1	138.7051	-0.47	31290	350.7	89.2
Roof	138.8232	-0.38	32723	287.1	114.0
F_{int}	136.1665	-2.29	209005	1716.4	121.8
W_{ext}	137.2067	-1.54	112748	1156.8	97.5
W_{int}	137.4554	-1.36	120615	1023.0	117.9
F_1+Roof+F_{int}+W_{ext}+W_{int}	131.9721	-5.30	506381	3973.0	127.5

Table 7.18 Results of retrofit measures combinations on LR Before 2002 typology with new AC units and additional insulation on all building envelope elements installed

As it could be seen from the results, the full insulation retrofit package brought down the total energy consumption by a percentage that was higher than any of the individual retrofit actions. However, the annual financial savings caused by energy demand decrease could not repay for the IIC during the 50 years of service. Considering the PBP this package, as was expected, performed worse than any of the individual options since its PBP was the highest. These findings prove the idea, that if individual retrofit measures focused on decreasing a certain type of energy use (e.g. heating and cooling) were not financially viable, integration of several of them would not be economically beneficial either. It also supports the proposed methodology of retrofit measures evaluation based on a ranking system and their ranked integration.

One of the building parameters that was changed via the integration of all insulating retrofit measures but could not be economically or environmentally accounted for directly using the proposed methodology was the passive change of the indoor thermal environment. Figures 7.3 and 7.4 presented the indoor temperature variations (red lines) during one simulation year for an LR building built before 2002 with no retrofits performed (Figure 7.3) and with insulation added to all of the building elements (Figure 7.4). The regression trend (blue line) showed that during winter the indoor temperature variations stayed closer to the comfortable 18°C threshold in the insulated building than in non-insulated one. The thicker walls and additional insulation provided by the retrofit measures stored more heat in the fabrics and slowed down the cooling of the materials. Thus, during the cold months' period, insulation decreased the heating energy consumption and maintained warmer indoor temperatures between the heating system usages. A more comfortable indoor environment increases the overall satisfaction of residents with their living spaces and is also associated with improved productivity, increased happiness and on average sustaining better health, while uncomfortable temperatures, especially cold, was found to lead to cardiovascular diseases (Barnett et al., 2007, Fisk and Rosenfeld, 1997, Hsee et al., 2009, Keatinge et al., 1997, Tanabe et al., 2007, Umishio et al., 2019). Based on this, it could be said that the additional building insulation provides non-financial benefits to the residents. However, comparing Figure 7.3's and Figure 7.4's regression trend during the summer months it showed that the indoor temperature variations were on the hotter side in an insulated building. The reasoning behind it was probably the same as for temperature increase during winter months: thicker walls and more insulation stored more heat and were cooling down more slowly. Thus, additional insulation had the potential to improve the indoor environment in one season of a year while also worsening it in the other season. For any future research where the insulation retrofit measures were to be found economically and environmentally viable options, these indoor temperature changes could be balanced and improved with other retrofit measures that were evaluated to be uneconomical in this research (e.g. shading devices, Low-E coated windows, etc).

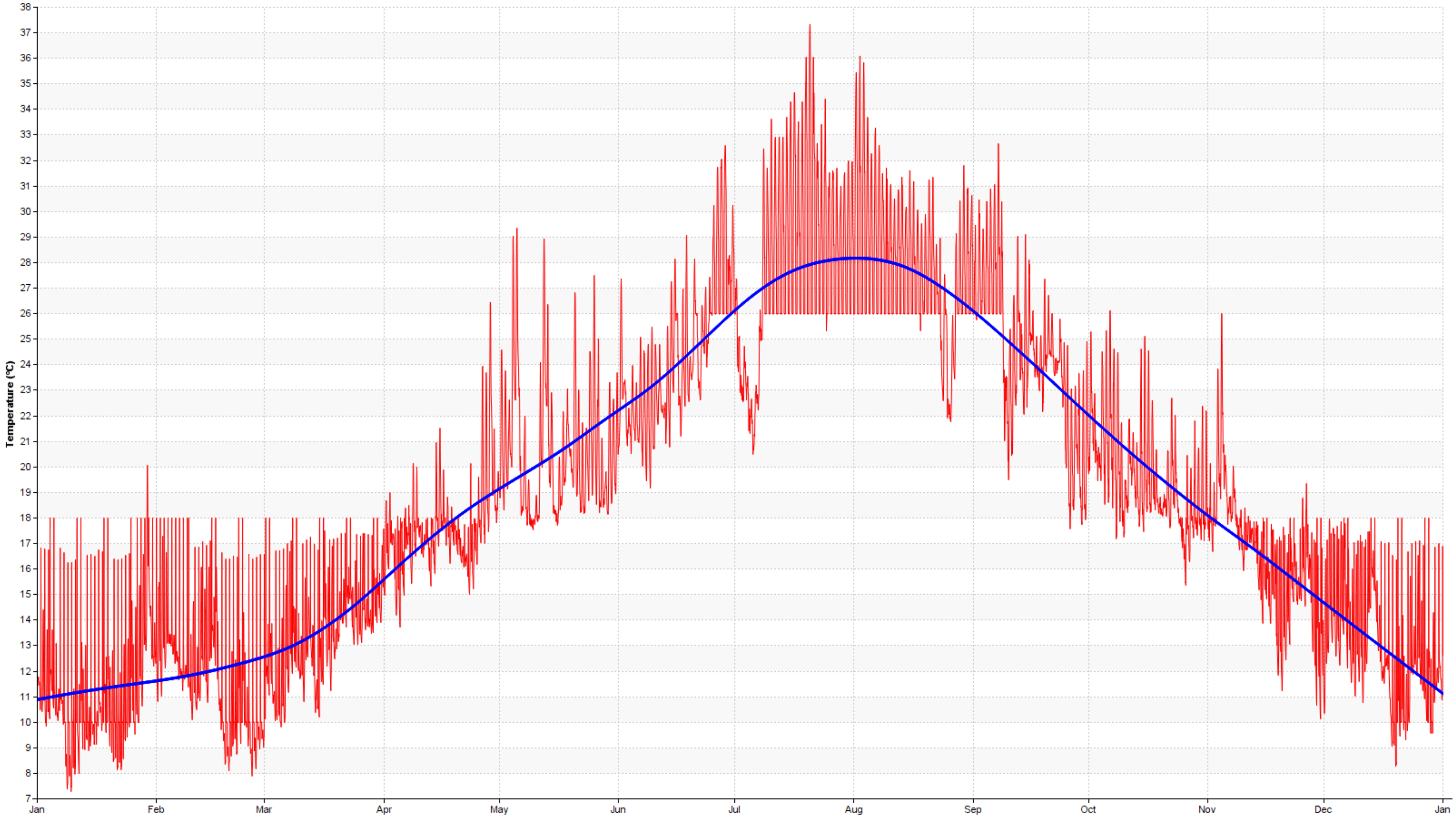


Figure 7.3 Annual indoor temperatures variations in LR Before 2002 with no additional insulation installed

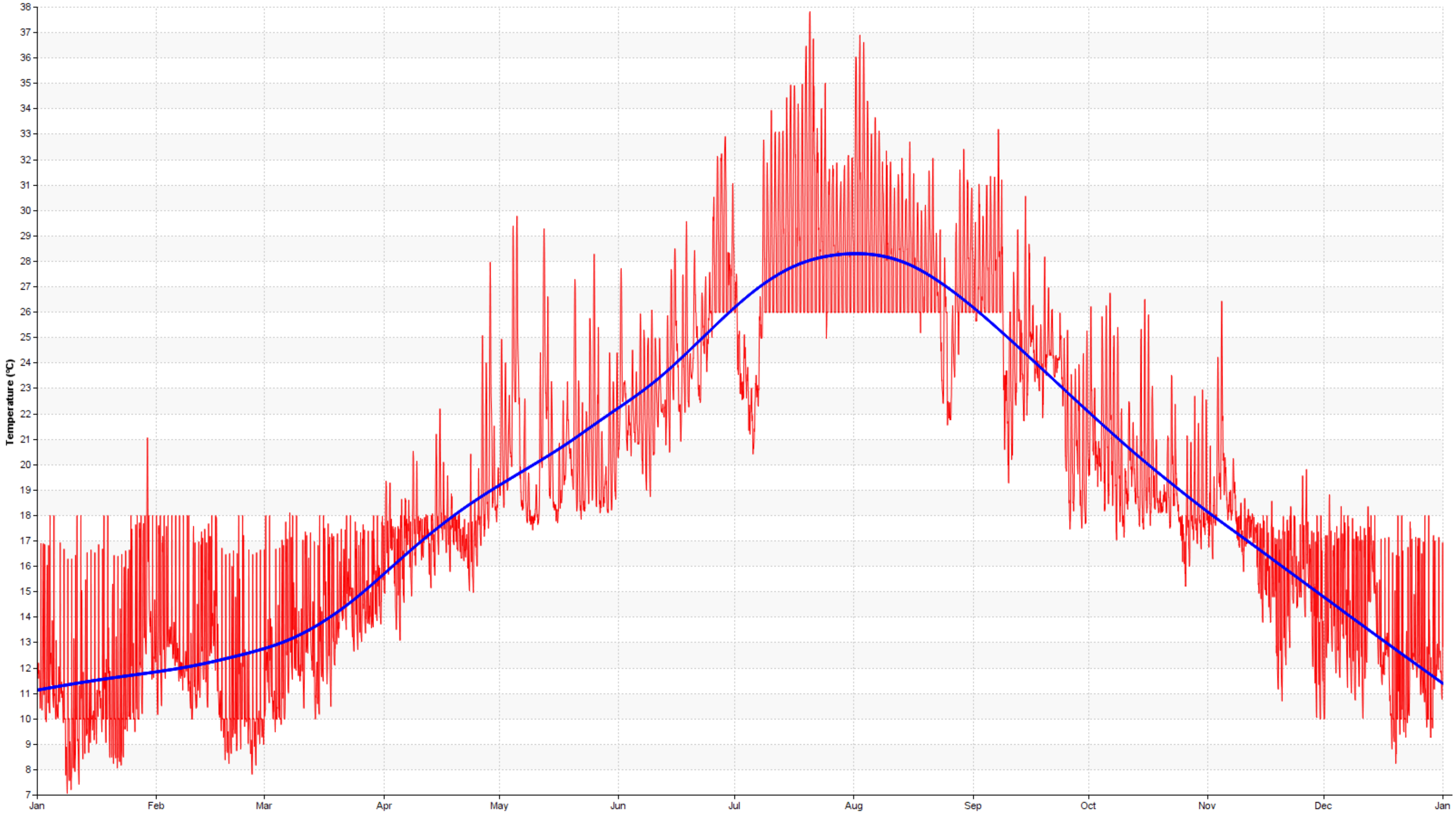


Figure 7.4 Annual indoor temperatures variations in LR Before 2002 with additional insulation installed

7.4.3 Final retrofit packages

Considering all of the building retrofit measures evaluation discussed above, the final retrofit packages consisted only of the retrofit actions that were found to be economically and environmentally beneficial in case of their individual and combinatorial application. The energy, financial, and environmental performances of each of the final individual retrofit measures are presented in Figures 7.5-7.8. Ranked combinations of final individual retrofit measures and different stages of their integration were presented in Table 7.19.

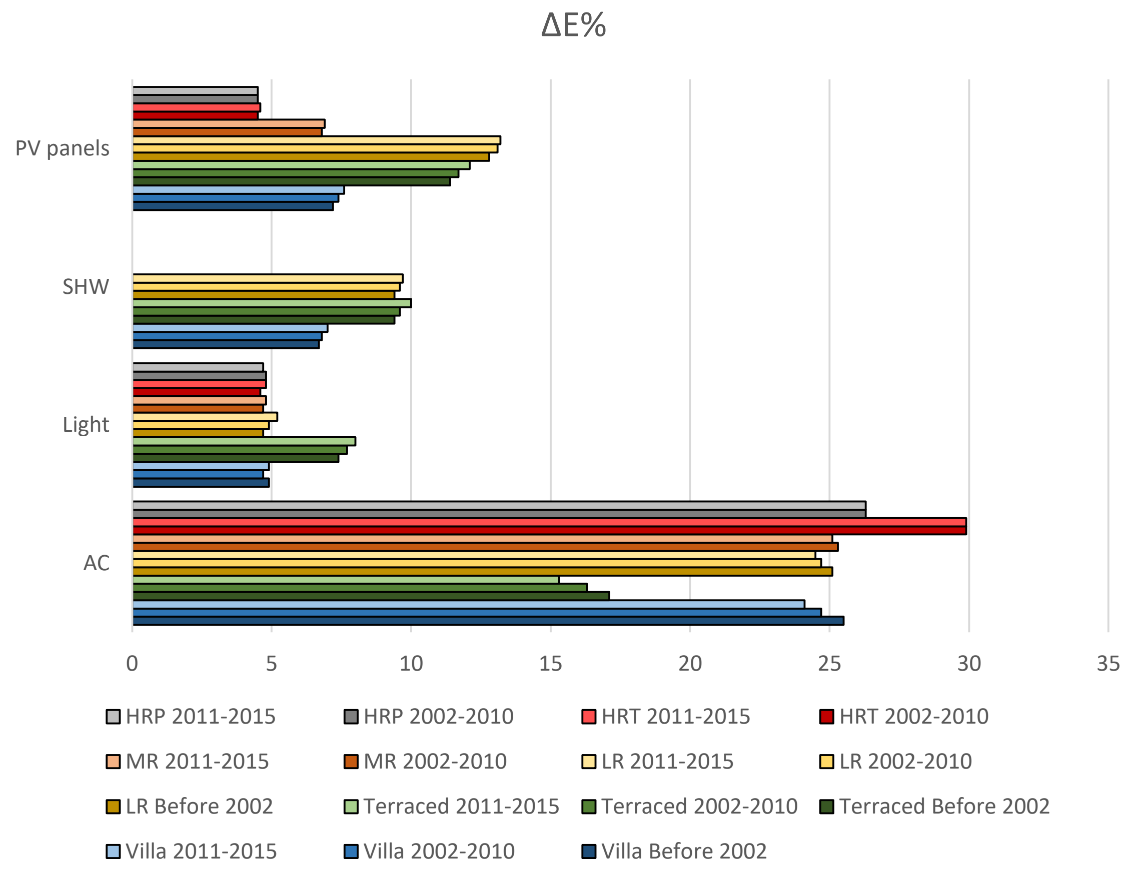


Figure 7.5 Comparison of $\Delta E^{\%}$ of final individual retrofit measures on all building typologies

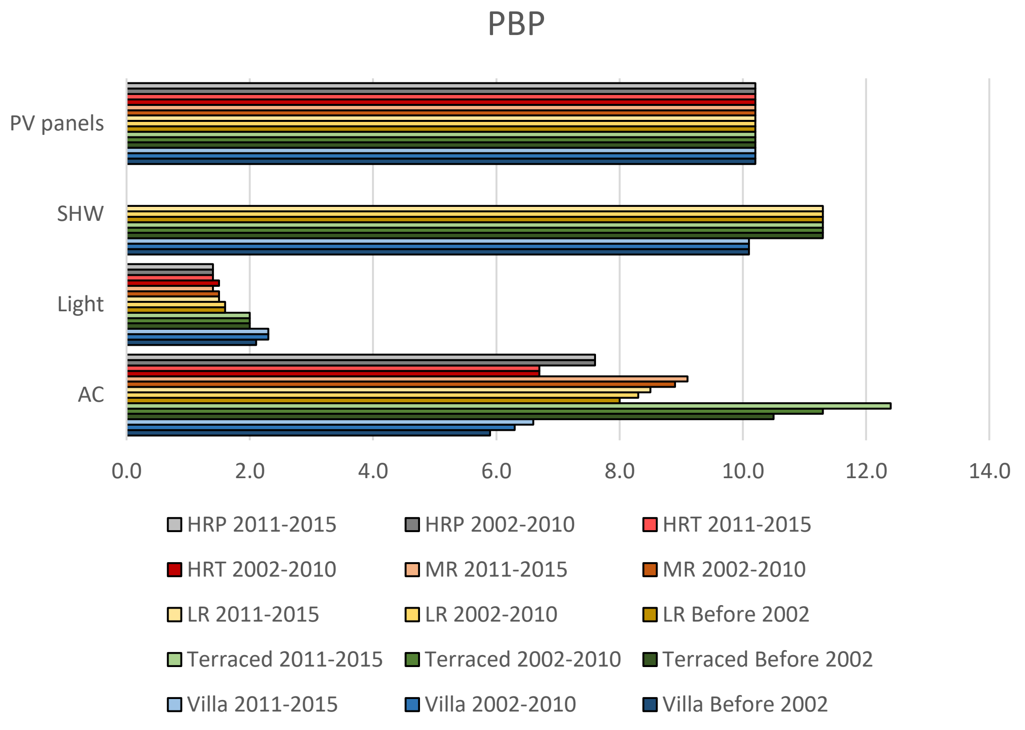


Figure 7.6 Comparison of PBP of final individual retrofit measures on all building typologies

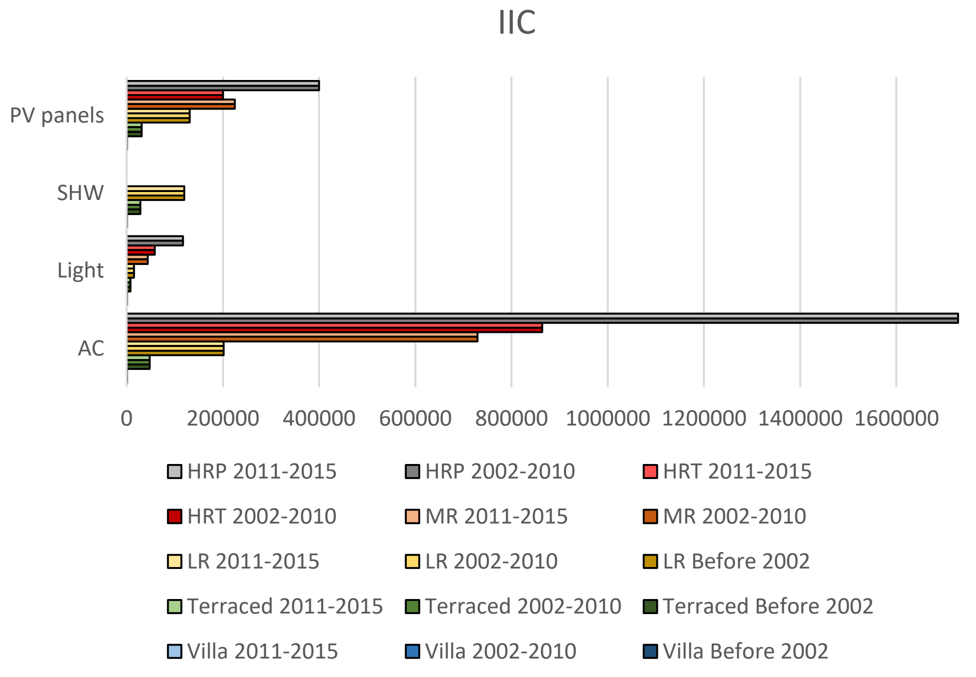


Figure 7.7 Comparison of ICC of final individual retrofit measures on all building typologies

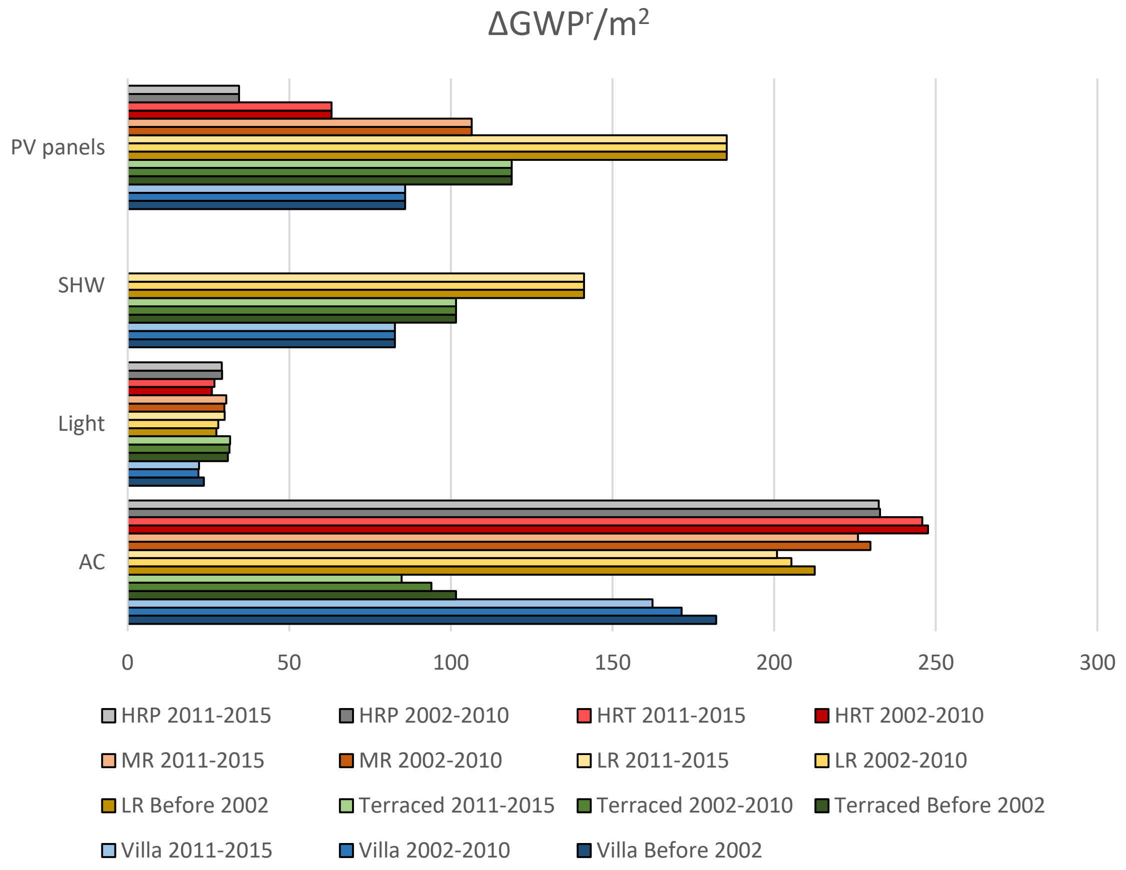


Figure 7.8 Comparison of $\Delta GWP^r/m^2$ of final individual retrofit measures on all building typologies (ΔGWP^r calculated based on RM's service life)

Villa Before 2002	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	170087.6	170087.6
Stage 1	+	-	-	-	12800	126773.244	139573.244
Stage 2	+	+	-	-	14569	118423.5	132992.5
Stage 3	+	+	+	-	20819	106184	127003
Stage 4	+	+	+	+	26519	94852.63	121371.6
Villa 2002-2010	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	165582.4	165582.4
Stage 1	+	-	-	-	12800	124667.5	137467.5
Stage 2	+	+	-	-	14569	116888	131457
Stage 3	+	+	+	-	20819	104648.5	125467.5
Stage 4	+	+	+	+	26519	93317.18	119836.2

Villa 2011-2015	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	161027.7	161027.7
Stage 1	+	-	-	-	12800	122147.5	134947.5
Stage 2	+	+	-	-	14569	114306.7	128875.7
Stage 3	+	+	+	-	20819	102067.2	122886.2
Stage 4	+	+	+	+	26519	90735.85	117254.9

Terraced Before 2002	**LED**	**AC**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	534859.2	534859.2
Stage 1	+	-	-	-	7930	495251.6	503181.6
Stage 2	+	+	-	-	55930	403861.5	459791.5
Stage 3	+	+	+	-	87180	342664	429844
Stage 4	+	+	+	+	115680	292270.7	407950.7

Terraced 2002-2010	**LED**	**AC**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	522803.7	522803.7
Stage 1	+	-	-	-	7930	482597.8	490527.8
Stage 2	+	+	-	-	55930	397403.4	453333.4
Stage 3	+	+	+	-	87180	336205.9	423385.9
Stage 4	+	+	+	+	115680	285812.5	401492.5

Terraced 2011-2015	**LED**	**AC**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	506365.6	506365.6
Stage 1	+	-	-	-	7930	465951	473881
Stage 2	+	+	-	-	55930	388227.3	444157.3
Stage 3	+	+	+	-	87180	327029.8	414209.8
Stage 4	+	+	+	+	115680	276636.4	392316.4

LR Before 2002	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	2002119	2002119
Stage 1	+	-	-	-	201600	1499480	1701080
Stage 2	+	+	-	-	216545	1405865	1622410
Stage 3	+	+	+	-	347795	1148836	1496631
Stage 4	+	+	+	+	467495	959816.7	1427312

LR 2002-2010	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	1967098	1967098
Stage 1	+	-	-	-	201600	1480290	1681890
Stage 2	+	+	-	-	216545	1384648	1601193
Stage 3	+	+	+	-	347795	1127619	1475414
Stage 4	+	+	+	+	467495	938600.2	1406095

LR 2011-2015	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	1945299	1945299
Stage 1	+	-	-	-	201600	1468289	1669889
Stage 2	+	+	-	-	216545	1366382	1582927

Stage 3	+	+	+	-	347795	1109353	1457148
Stage 4	+	+	+	+	467495	920334	1387829
MR 2002-2010	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	6466931	6466931
Stage 1	+	-	-	-	729600	4831611	5561211
Stage 2	+	+	-	-	773642	4528561	5302203
Stage 3	+	+	+	-	998642	4087939	5086581
MR 2011-2015	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	6405495	6405495
Stage 1	+	-	-	-	729600	4795172	5524772
Stage 2	+	+	-	-	773642	4486423	5260065
Stage 3	+	+	+	-	998642	4045801	5044443
HRT 2002-2010	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	8655100	8655100
Stage 1	+	-	-	-	864000	6070080	6934080
Stage 2	+	+	-	-	922560	5674068	6596628
Stage 3	+	+	+	-	1122560	5282404	6404964
HRT 2011-2015	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	8591892	8591892
Stage 1	+	-	-	-	864000	6025247	6889247
Stage 2	+	+	-	-	922560	5617112	6539672
Stage 3	+	+	+	-	1122560	5225448	6348008
HRP 2002-2010	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	17295441	17295441
Stage 1	+	-	-	-	1728000	12744667	14472667
Stage 2	+	+	-	-	1845120	11920993	13766113
Stage 3	+	+	+	-	2245120	11137665	13382785
HRP 2011-2015	**AC**	**LED**	**PV**	**SHW**	**IIC**	**NPV**	**LCC**
No intervention					0	17270002	17270002
Stage 1	+	-	-	-	1728000	12727171	14455171
Stage 2	+	+	-	-	1845120	11907428	13752548
Stage 3	+	+	+	-	2245120	11124100	13369220

Table 7.19 Financial evaluation of final individual retrofit measures combinations

Thus, for all of the building typologies except for the Terraced houses form it was advised to prioritise the replacement of old AC units first as this retrofit measure brought down the heating and cooling energy consumption dramatically. After that, it was proposed to perform a full substitution of old inefficient light bulbs with LED ones. For the Terraced buildings, the priority of retrofit measures was the opposite starting from lights replacement and proceeding with AC upgrade. With these two retrofit measures installed the next advised action was to install PV panels on the roofs of all of the building typologies. And finally, if the finances allowed, it could be proposed to integrate evacuated tubes solar hot water collectors on Villas, Terraced and LR building forms.

As discussed in Chapter 4, the best financially performing retrofit package can be found by determining the minimum LCC. For each of the analysed typologies, the minimum LCC is achieved when all final individual retrofit measures are installed. The reductions in NPV driven by energy consumption decreases outweigh the IIC for each of the subsequent retrofit measure installations, which can be observed on Figure 7.9. The rejection of retrofit measures that had PBP greater than their expected service life ensured a consistent decline in LCC with the increase of the number of installed retrofit measures. Based on these results, the optimum retrofit packages for each typology were defined and further verified using IES-VE to perform simulations of fully retrofitted buildings. The results of these simulations were shown in Table 7.20.

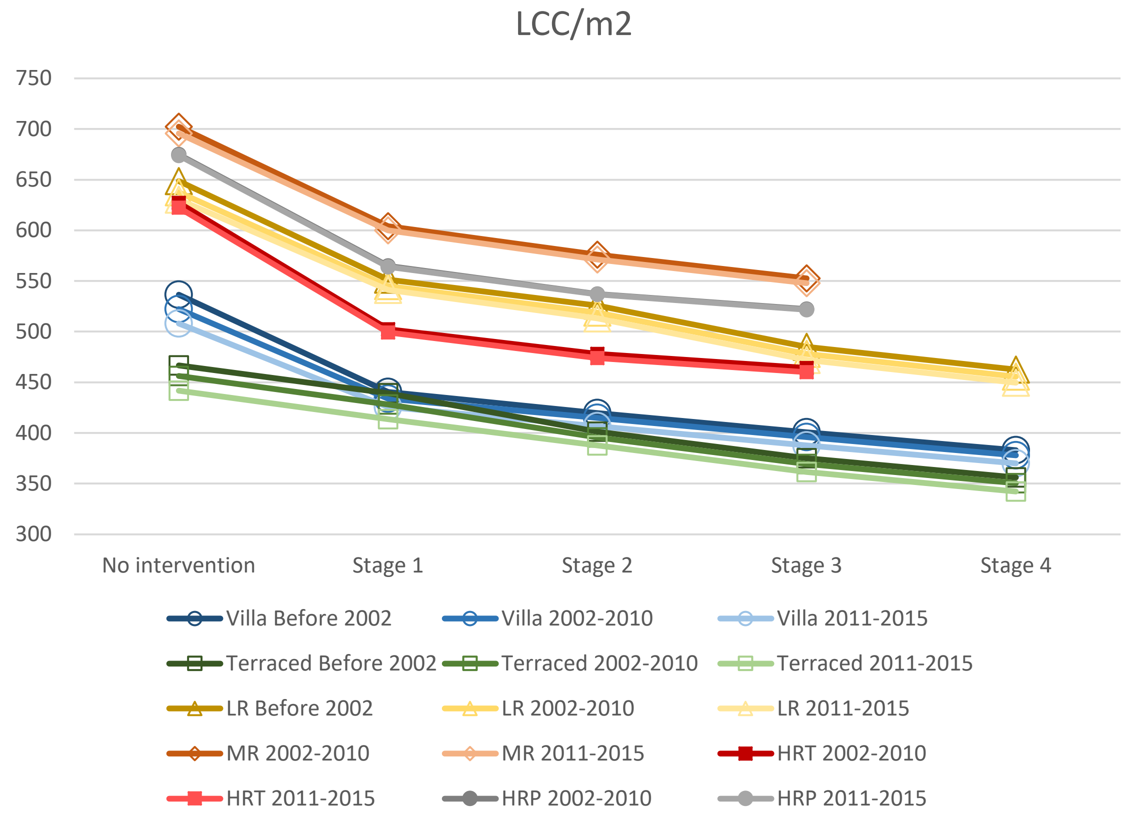


Figure 7.9 Overview of change in LCC for each building typology through different stages of retrofit measures integration

	Retrofit measures ranks								
	1	2	3	4	E_{total}, MWh	$\Delta E^{\%}$	$S_{\Delta E}$, RMB	IIC, RMB	ΔGWP^{r}, $kgCO_{2eq}$
Villa Before 2002	AC replacement	LED lights	PV panels	SHW	8.7941	-44.4%	3773	25634	-65328
Villa 2002-2010	AC replacement	LED lights	PV panels	SHW	8.6287	-43.9%	3637	25634	-62769
Villa 2011-2015	AC replacement	LED lights	PV panels	SHW	8.3917	-43.9%	3537	25634	-60887
Terraced Before 2002	LED lights	AC replacement	PV panels	SHW	27.0540	-45.6%	12188	111715	-205560
Terraced 2002-2010	LED lights	AC replacement	PV panels	SHW	26.4505	-45.6%	11910	111715	-200339
Terraced 2011-2015	LED lights	AC replacement	PV panels	SHW	25.5934	-45.6%	11549	111715	-193566
LR Before 2002	AC replacement	LED lights	PV panels	SHW	88.5933	-52.4%	52443	460023	-890645
LR 2002-2010	AC replacement	LED lights	PV panels	SHW	86.7111	-52.6%	51704	460023	-876783
LR 2011-2015	AC replacement	LED lights	PV panels	SHW	85.2978	-52.8%	51375	460023	-870596
MR 2002-2010	AC replacement	LED lights	PV panels	-	377.9258	-37.1%	120022	976621	-2003570
MR 2011-2015	AC replacement	LED lights	PV panels	-	374.2445	-37.1%	118931	976621	-1983084
HRT 2002-2010	AC replacement	LED lights	PV panels	-	526.3810	-34.6%	149562	1093280	-2526670
HRT 2011-2015	AC replacement	LED lights	PV panels	-	521.5538	-34.7%	148999	1093280	-2516094
HRP 2002-2015	AC replacement	LED lights	PV panels	-	1104.8100	-31.3%	270384	2186560	-4513802
HRP 2011-2015	AC replacement	LED lights	PV panels	-	1103.2991	-31.3%	269925	2186560	-4505184

Table 7.20 Optimal retrofit packages for each developed building typology

In combination, these retrofit measures could decrease the total building energy consumption by 30%-50% depending on the building typology. LR buildings were found to benefit the most out of all building forms (52.4%-52.8% expected energy decreases) since they had relatively high EUI similar to the MR and both of the HR building forms, and had all four of the proposed activities integrated. The smallest energy demand changes were observed in HRP building forms with 31.3% energy reductions. This could be explained by the proposal to not consider SHW systems for these building typologies similar to the MR and HRT, which, as a result also showed smaller energy decreases than LR buildings. This situation was further exacerbated by not having enough roof space to install the same amount of PV panels per household as for Villas, Terraced houses and LR buildings.

The number of individual retrofit measures in these retrofit packages was smaller than in other residential buildings retrofit researches that suggested window replacement, additional insulation, shading devices, etc. Some of the reasoning behind this was already addressed in previous sections as being primarily attributed to the unique human behaviour and intermittent localised heating and cooling. However, the economical impracticality of these retrofit measures was additionally intensified by cheap electricity prices in China. This problem was also observed in Ouyang et al. (2009) where the majority of typical building retrofit measures were found to be economically unviable to implement considering actual building usage patterns. According to their results, “low energy price hampers energy-saving implementations’ in buildings. This emphasizes the importance of government subsidies that could decrease the IIC of retrofit measures and encourage the residents and property management companies to consider introducing retrofits to their communities.

Overall, based on the annual financial savings coming from the energy demand reductions presented by retrofit packages implementation and the IIC, the PBP of the proposed retrofit packages for all building typologies was below 10 years. Considering that the expected service life of these retrofits varied between 10 years (LED lights) and 25 years (PV panels and SHW), these retrofit actions proved to be a good financial investment that will not only pay off but also accumulate financial savings during the years of service. The IIC of these packages depended on the building form with the smallest building's (Villa) IIC being 25634 RMB and the largest building's (HRP) almost 2.2 million RMB. Considering these prices per household, Villa's retrofits were the most expensive one, while HRT building forms presented the smallest IIC per household of 11755.7 RMB.

In addition to the financial savings discussed above, in those ten years, the amounts of GHG emissions saved due to energy consumption decreases would drastically surpass the amounts of GHG associated with equipment manufacturing and materials extraction. Figure 7.10 presents the overview of total GWP reductions in building typologies with final retrofit package installed during the first ten years of operation. It should be noted, that for AC, PV panels and SHW the service life exceeds 10 years, and therefore, greater reductions can be expected. These energy demand and GHG production decreases would remove some of the tension currently placed on China's energy-producing sector and simultaneously partially decarbonise the residential sector. Thus, these changes would be necessary to mitigate climate change, decrease the depletion of Earth's natural resources, and indirectly improve the air quality.

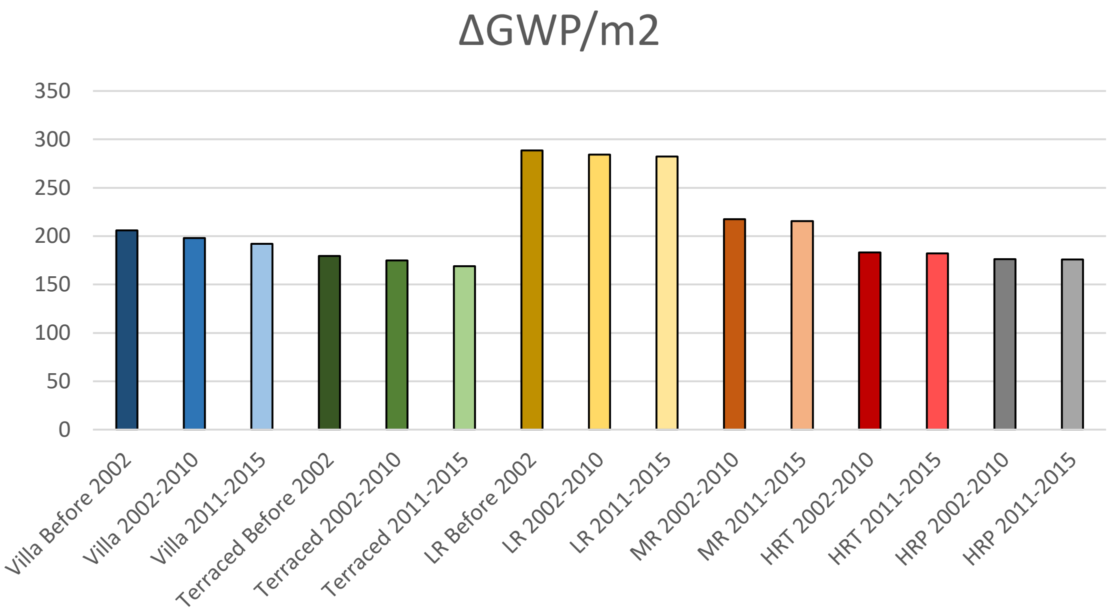


Figure 7.10 Reductions in GWP during 10 years of operation for each building typology with full integration of final retrofit packages

7.5 Conclusion

The extent to which various individual building retrofit measures influence the total building energy demand and how they interact with each other can be different. Therefore, for accurate estimation of optimal retrofit scenario and its financial and environmental benefits, it is essential to account for individual measures' interaction. Thus, this chapter applied developed in Chapter 4 EE Score assessment framework on 12 passive and active systems retrofits with all of their proposed variations to determine the best-fit retrofits for Ningbo city’s residential typologies.

The first part of this chapter discussed all the evaluated individual building retrofit measures and financial and environmental empirical data collected on them such as their market prices in China and manufacturing and material extraction energy implications associated with them. This data was important to perform a cost-effectiveness and environmental consequences evaluation of each of those retrofit activities. Energy simulation of 12 individual suggested building retrofit measures was performed on each of the 15 evaluated building typologies. The Economic-Environment analysis was performed for each of the retrofit actions and they were further ranked based on their EE Score.

Implementation of these individual retrofit measures on buildings constructed during different periods (and consequently possessing different thermal performance) allowed for a deeper understanding of the possible interaction and influence of retrofit activities on each other. The simulation of combinations of retrofits with one-by-one installation based on their rank with financial evaluation on each step revealed that after the replacement of AC units (which was the highest priority retrofit measure based on individual retrofit measures’ EE Score) all of the building envelope insulation retrofits for all of the building typologies were financially unviable with PBP higher than the expected service life. Considering the local heating and cooling systems usage patterns, the only economically beneficial retrofit activities were AC replacement, LED light bulbs installation, and PV panels and evacuated tubes solar collectors integration on the roofs of the buildings. These activities had little to no interaction between each other and collectively they could bring the total building energy demand by 30%-50% depending on the building typology, which, consequently, would result in millions of tons of GHG emissions reductions for some of those buildings in a decade.

Based on these results and LCC analysis of final retrofit packages, the most optimal retrofit scenario for each building typology was determined. Following the proposed EE Score assessment framework allowed to drastically decrease the amount of necessary computational simulations (from more than 64 million to less than 1000) to assess the retrofit measures and their interactions. This was achieved due to the proposed rejection of underperforming individual retrofit measures (based on their PBP) on each simulation iteration. The implemented EE Score assessment framework was also validated through a case scenario where all individual retrofit measures that underperformed based on the EE Score assessment framework were installed on the building and simulated. The results of this validation proved the EE Score assessment framework to be a reliable, flexible, and useful tool to determine the best retrofit solution in the presence of many proposed retrofit measures variations. It decreased the total amount of required simulations without the loss of valuable information.

The results of the EE Score assessment framework presented in this chapter assists in the decision-making process of residential retrofits. It can be used by the local and national governments to manage the residential retrofits and direct financial support in the most beneficial course. In addition to that, it can provide help in establishing further financial incentives to residential retrofits in the most productive way. The proposed optimal retrofit packages and final individual retrofit measures comprising them can be installed all at once or on a singular basis, which makes the ICC of the retrofits lower and easier to afford for the residents. Direct and easy to understand and implement step-by-step retrofit actions simplifies the engagement of the public into the retrofit projects and ensures their higher success rates.

8 Chapter 8. Conclusion

This chapter outlines the conclusions of this research project and highlights its innovation and application in the industry and other studies. It concludes by critically evaluating the research, stating its limitations and barriers and providing suggestions for further development.

8.1 Concluding remarks

This project aimed to evaluate the cost-effectiveness and environmental benefits of the HSCW climate zone's residential building stock retrofits and present the most suitable retrofitting scenarios, which had been achieved. As it was outlined in Chapter 1 and discussed more closely in Chapter 2, the environmental problems associated with immense energy and materials consumption required to improve the energy performance of existing building stock. The shift must be made from demolishing old buildings and building new energy-standards-abiding buildings to retrofitting old poorly performing buildings. However, the decision-making process regarding the exact retrofit measures that would be financially and environmentally beneficial is complex and challenging. The final energy consumption of the building and consequently the results of energy retrofits depend on numerous variables such as building type, height, form, shape, construction materials, heating and cooling systems, occupancy profiles, residents' interaction with building services and their preferences, etc. Due to this, all of these variables must be verified and accounted for during the retrofit measures' performance evaluation, while the decision on selection of retrofit measures to be installed must be done with careful consideration about suitable economic and environmental parameters.

To achieve the outlined aim, this research project was executed in four main steps including the Ningbo municipality’s residential building stock analysis, occupancy data collection, reference building models development and verification, and retrofit measures evaluation and selection. The results of each one of these steps can represent a separate study on itself and be used and expanded further in other research. At the same time, the execution of the first three steps was essential for the final part of this thesis to take place since it was built upon the results of the first three parts.

The residential building stock analysis was carried out via mainly quantitative empirical and analytical research methods. Stratified random sampling was executed on Ningbo city’s residential building stock with construction period used as the stratifying variable. With this sampling method, 18 residential building communities were selected and data on their buildings were collected employing online observations and on-site measurements. Using a two-step cluster analysis, 6 building form groups were established from the 18 sampled residential building communities. Empirical data from local and national standards were used for the creation of representative building form models with thermal performance close to the existing analysed buildings.

To collect the data on heating and cooling occupancy behaviour and actual energy consumption, a questionnaire survey was executed. Mixed (combined qualitative and quantitative) analytical and descriptive research methods were used in this part of the study. The questions were distributed randomly both online and on-site to willing participants living in urban areas of Ningbo municipality. The collected answers to these questions provided necessary information about the type and amount of heating and cooling equipment, frequency and time of the day when occupants preferred to use heating and cooling systems, and monthly electricity and gas bills. This information was further used to produce occupancy profiles for the building energy models representative of local behaviour. The building form models and building energy models were combined to develop final representative building models for each of the analysed building typologies. These models were verified through energy simulation implemented with IES-VE software by comparing the simulated EUIs with the ones reported by participants in the questionnaire survey.

The final part of this research was to use the established building models (that are representative of Ningbo's residential building stock and local occupancy parameters) and examine the benefits of integrating different retrofit measures into these buildings. Various interventions into 12 passive and active building systems were suggested and evaluated considering their individual and combinatorial installation. The following parameters were used as the economic and environmental indicators of retrofit measures performance: PBP, IIC, $S_{\Delta E}$, and ΔGHG^{r}. To evaluate the results of retrofit scenarios and decrease the amount of necessary combinatorial simulations, the EE Scoring assessment framework was developed that ranked the individual retrofit measures by their benefits while rejecting the ineffective measures. Following the established framework and LCC analysis results, the most efficient retrofit packages for each analysed typologies were determined and their economic and environmental effects were evaluated.

Overall, an in-depth evaluation of suitable for HSCW climate zone (Ningbo municipality in particular) retrofit measures was performed with the best-fit scenarios established. The outcomes of this research include:

- Residential building typologies for Ningbo city;
- Occupancy, heating and cooling profiles and thermal preferences for HSCW climate zone and Ningbo in particular;
- EUIs of Ningbo city's residential buildings;
- EE Scoring assessment framework;
- The most cost-effective and environmentally beneficial retrofit packages for Ningbo city's residential building stock.

8.2 Innovation and application of this research

This section discusses the novelty, significance and application of this study.

8.2.1 Residential building typologies for Ningbo city

At its initial stages, this research faced the challenge of low data availability on the residential building stock of Ningbo municipality. No prior research was done to analyse the residential building stock of Ningbo city on a macro scale, and little research was available on the HSCW climate zone that could be useful for this research. To solve these issues, various publicly available data sources were used such as expert knowledge (in the form of local and national building standards), on-site measurements, and online sources (orthorectified satellite imagery viewed in GIS, search engines such as Google and Baidu). This data was further analysed and segregated using two-step cluster analysis into 6 building form groups that were further stratified based on the year of construction into 21 building typologies.

By doing so, this research proposes a city-scale building data collection process that can be used in a low-data availability scenario in any place of interest in the world. It also proposes a methodology for analysis of this data and building classification based on evaluated characteristics (which can be similar to this research or different depending on the building stock's variability and research scope and direction). Finally, the development of building typologies representative of Ningbo municipality's residential building stock presents a comprehensive overview of the city's buildings and provides a foundation for other studies. The decision of developing the models in BIM software opens limitless possibilities of expanding the useful information provided by models through their integration with GIS, energy simulation, sensors, decision-making models, construction planning, material and cost analysis, etc. Combining these typologies with GIS would provide urban planners, city facilities engineers, and government with urban-scale residential building stock maps assisting in the visualization purposes.

8.2.2 Occupancy, heating and cooling profiles

During the literature review on necessary data for building energy simulation (Chapter 2), it became clear that for accurate energy consumption calculations the occupancy behaviour and residents' thermal preferences are essential. Numerous research had been done to determine that if occupants are not accounted for in the simulation, the difference between the simulated and actual energy demand can be significant. However, accurate occupancy profiles are rarely included in the retrofit scenarios evaluation research, which can result in overestimation of energy decreases brought by retrofits. For intermittently heated and cooled buildings in the HSCW climate zone inclusion of accurate occupancy schedules and thermal preferences is detrimental, but no data on this is available and no research has been done on residential occupancy in Ningbo municipality.

This research implemented a questionnaire survey (discussed in Chapter 6) to collect data on heating and cooling schedules and systems. The questions inquired about the frequency and time of the day when occupants preferred to use these building services. Collected replies were used in this study during the building energy simulation and retrofit scenarios simulation. Based on the results of simulations, this research highlighted the importance of using heating and cooling schedules present in the residential buildings in the retrofit measures evaluation research. In addition to that, gathered information on residents' preferences in the HSCW zone can be used in other research where occupancy behaviours in similar climate conditions are of importance. They could also assist government representatives of Ningbo municipality and building compounds facility managers in the development of guidelines for promoting energy-conserving behaviours among residents. Based on these results, decisions can be made regarding adjustments in occupancy regimes and thermal requirements.

8.2.3 EUI's of Ningbo municipality's residential buildings

Similarly to the collection of occupancy behaviour data, the reported energy consumption in residential buildings of Ningbo municipality was collected via a questionnaire survey. Though this data is not useful to the government representatives or building compounds managing companies (as they possess actual more accurate data on building energy demand, but could not share it for privacy reasons), it could be valuable for other researchers that are interested in studying Ningbo's residential building stock. The methods to collect this data proposed and implemented here can be applied to other places where similar challenges are faced.

8.2.4 EE Scoring assessment framework

Based on the literature review, the most commonly considered groups of variables in retrofit decision-making are energy, emissions reductions, and financial parameters. Some studies implement only one parameter from these groups, while others include many creating a complex multi-objective problem. This research was focused on the inclusion of all three groups of parameters into its consideration during retrofit selection to provide optimum cost-effective and environmentally beneficial suggestions.

Considering the number of building services systems that were initially proposed to be retrofitted and the great number of individual retrofit measures variations, a combinatorial simulation of all possible combinations of these variations was impossible to achieve. Therefore, to address this issue and consider the three groups of decision-making parameters for retrofit selection discussed above, a novel EE Scoring assessment framework was developed. It comprised the analytical methods of LCA and LCC analysis for determination of retrofit measure's performance and rejected the ineffective candidates drastically decreasing the required amount of combinatorial retrofit simulations. The verification of its results was done on a case study building by simulating the installation of all individual retrofit measures (including the ones deemed ineffective by the framework) and evaluating this retrofit's performance.

Overall, the developed retrofit assessment framework proved to be effective and essential for the completion of this study. It can be implemented by stakeholders and government representatives to guide them in the decision-making process. Its contribution can be also applicable in other research to evaluate various building designs and retrofit scenarios for other city's building stock or other building types.

8.2.5 Cost-effective and environmentally beneficial retrofit packages

Application of EE Scoring assessment framework and LCC analysis on 15 examined building typologies helped to establish Ningbo city's building retrofit solutions for decreasing the total energy consumption of the buildings. Since the main decision-making parameters were global warming potential decrease, small initial cost, and high annual financial savings, the final retrofit packages are affordable, cost-effective, provide a financial return on the investment, and reduce the GHG emissions. Results presented here can be applied by homeowners, stakeholders, government, and facility managing companies to decrease energy consumption in the buildings, improve the indoor environment and partially decarbonise this industry sector.

8.3 Limitations and future work

A generalisation of this thesis' findings is difficult due to its case-study approach and the variability of building stock and the AEC industry in general. Nonetheless, the methods used here to achieve the research aim and obtain the findings can apply to other building research projects. These implemented research methods were selected with consideration of their applicability, research aim, and available data. Thus, in similar cases, developed methods can be used as-is, but can also be improved upon to add robustness to the study and decrease some of the present uncertainties. Existing limitations of this research as well as suggestions for future research improvements are discussed below.

8.3.1 Residential building stock sampling

The development of residential building typologies was limited by the executed sampling method to 385 buildings from 18 residential communities. While the number of analysed buildings was argued to be sufficient to represent Ningbo municipality's residential building stock, the variability of residential communities could be increased in future research. As it was discussed in Chapter 5, buildings in the same residential community tend to possess similar characteristics such as layout, form, shape, and height. Thus, including more buildings from other communities in the analysis would provide higher variability and robustness to the study.

8.3.2 Questionnaire survey sampling, execution, and results interpretation

The collection of occupancy data via questionnaire survey was restricted by its sampling nature to the number of obtained replies. For future research, this survey is suggested to be expanded to a greater number of participants and possible stratification of replies based on the developed typologies. This would allow to create different occupancy behaviour profiles for different typologies more representative of the actual behaviour in these building types. In addition to that, it is suggested to run an all-year-around questionnaire survey executed on a seasonal or even monthly basis. This approach would eliminate the possibility of respondents' inaccurate recall of data from a long period ago and consequently improve the reliability of results.

8.3.3 LCC results variability with time

Economical parameters used in this research to perform LCC analysis include time-dependent variables such as the discount rate, annual energy price increase, inflation, interest rate, change of material and labour prices, etc. Even though these limitations might cause discrepancies between the current retrofit assessment and the same assessment performed in the future, the methods implemented here are valid and the results are representative of the current state of economical evaluation. In future research, it is suggested to adjust financial variables according to the future values. Additionally, the boundaries established in this research excluded the operation and maintenance and disposal costs, which are suggested to be included in further research to add robustness and precision to the analysis.

8.3.4 Government incentives

This thesis excluded any governmental incentives towards a sustainable built environment from the financial evaluation of retrofits. Further research can be done on the existence of such programs and their inclusion in the financial analysis. Moreover, the results presented in this study provide a background for standards and regulations of residential building retrofitting practices in the HSCW climate zone. Future research can focus on the methods of how the government can promote and financially support the decarbonisation of the building sector.

8.3.5 LCA and environmental uncertainties

This research considered cradle to gate approach of the LCA method, meaning that the end of the life cycle of materials and equipment was excluded from analysis entirely. Such an approach limits the full understanding of the environmental influence of the retrofit measures selection process. In addition to that, the material extraction, delivery, and manufacturing processes are continuously improving both in terms of energy efficiency and emissions releases. Thus, to address these two issues in future research, it is suggested to implement cradle to grave analysis if possible and update the environmental data used in the analysis accordingly to the new practices. Moreover, other environmental parameters besides GHG emissions are suggested to be included in the LCA such as acidification, ozone depletion, etc.

8.3.6 Building energy simulation on macro-scale

On a macro scale (and on a city scale) buildings influence each other’s energy demand due to various passive interactions such as shading, glare, urban heat island effect, wind shielding and tunnelling, etc. These interactions bring uncertainties to individual building energy demand simulations. The decision to develop BIM models of representative buildings allows for their integration with GIS software to provide a macro-scale overview of the building energy simulation. Moreover, this would allow evaluating the possibility to perform macro-scale retrofits focused on residential communities rather than buildings. One of the possible directions of future research on this topic could be the utilisation of free surrounding space or free roof area from Villa, Terraced, and LR buildings to provide MR and HR buildings with on-site generated energy.

8.3.7 Practical validation of retrofits

Validation of retrofit measures selection in this research was executed with computational simulation. While it is a quicker, cheaper, and less time-consuming method to validate the results, the simulated energy differences brought by retrofits can differ from the actual ones. Thus, it is recommended to perform a practical application of final retrofit packages to validate them.

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Appendix A. Questionnaire

Participant Information Sheet

Building retrofit scenarios evaluation on urban scale based on BIM and GIS integration. A case study in Ningbo

Dear Participant,

Thank you for agreeing to participate in this questionnaire survey in connection with my PhD dissertation at the University of Nottingham Ningbo. The project is a study of residential buildings energy demand. It aims to develop a method to accurately estimate energy consumption of houses for the purpose of proposing an economical way to retrofit them.

Your participation in the survey is voluntary. You are able to withdraw from the survey at any time and to request that the information you have provided is not used in the project. Any information provided will be confidential. Your identity will not be disclosed in any use of the information you have supplied during the survey.

The research project has been reviewed according to the ethical review processes in place in the University of Nottingham Ningbo. These processes are governed by the University's Code of Research Conduct and Research Ethics. Should you have any question now or in the future, please contact me or my supervisor. Should you have concerns related to my conduct of the survey or research ethics, please contact my supervisor or the University's Ethics Committee.

Yours truly,

Polina Trofimova

Contact details

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UNNC Research Ethics Sub-Committee Coordinator: Ms Joanna Huang
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Participant Consent Form

Building retrofit scenarios evaluation on urban scale based on BIM and GIS integration. A case study in Ningbo

☐ I have read the Participant Information Sheet and the nature and purpose of the research project has been explained to me. I understand and agree to take part.

☐ I understand the purpose of the research project and my involvement in it.

☐ I understand that I may withdraw from the research project at any stage and that this will not affect my status now or in the future.

☐ I understand that the data collection will be recorded.

☐ I understand that while information gained during the study may be published, I will not be identified and my personal results will remain confidential.

☐ I understand that data will be stored in accordance with data protection laws.

☐ I understand that I may contact the researcher or supervisor if I require more information about the research, and that I may contact the Research Ethics Sub-Committee of the University of Nottingham, Ningbo if I wish to make a complaint related to my involvement in the research.

Signed ________________________________ Date _____________________

Contact details

Researcher:	Polina Trofimova	polina.trofimova@nottingham.edu.cn
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Questions

I have read the Participant Information Sheet and Participant Consent Form and agree to participate in this questionnaire. (Only for online version)

☐ I agree to participate ☐ I do not agree to participate

Thank you for participating in this questionnaire.

Please select the language. ☐ English

☐ Chinese

Building energy demand.

Q1. What is the area of your apartment? ________________________________ m^2

Q2. How many people (including you) live in the apartment? ________________

Q3. How many floors does the building you live in have? ___________________

Q4. What apartment community do you live in? (This information is required to check the year of construction of your building) __________________________________

Q5. What is your average monthly electricity bill?

In spring ________________RMB In summer ______________ RMB

In autumn _______________ RMB In winter ________________ RMB

Q6. Do you use gas?

☐ Yes

☐ No

Q7. What is your average monthly gas bill?

In spring ________________RMB

In summer ______________ RMB

In autumn _______________ RMB

In winter ________________ RMB

Summer occupant behaviour.

Q8. How many AC units do you have?

☐ 0

☐ 1

☐ 2

☐ 3

☐ 4

Q9. What is the most common time you use AC in summer? Select all suitable options:

☐ Never

☐ Night

☐ Morning (before work)

☐ Lunch break

☐ Evening (after work)

☐ All day

Q10. How often do you use AC in summer at night?

☐ Never

☐ Only in the hottest days (up to 2 weeks)

☐ For half of the summer

☐ All the summer

Q11. How often do use AC in summer during day-time?

☐ Never

☐ Only in the hottest days (up to 2 weeks)

☐ For half of the summer ☐ All the summer

Winter occupant behaviour.

Q12. What heating equipment do you use?

☐ Don’t use heating ☐ AC

☐ Floor heating ☐ Portable heaters (radiators or electrical fans)

☐ Other

Q13. If you have any other type of heating system in your apartment, please specify: ____

____

Q14. What is the most common time you use heating in winter? Select all suitable options:

☐ Never ☐ Night

☐ Morning (before work) ☐ Lunch break

☐ Evening (after work) ☐ All day

Q15. How often do you use heating in winter at night?

☐ Never ☐ Only in the coldest days (up to 2 weeks)

☐ For half of the winter ☐ All the winter

Q16. How often do you use heating in winter during day-time?

☐ Never ☐ Only in the coldest days (up to 2 weeks)

☐ For half of the winter ☐ All the winter

By clicking the "Submit" button below, you are consenting to participate in this study (for online version only).

☐ Submit ☐ Cancel