Evaluating Passivhaus EnerPHit Retrofit Strategies for Low-Rise Suburban Dwellings in China's Hot Summer - Cold Winter Climate Region

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy

by

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Declaration

I hereby certify that this thesis constitutes my own product, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions or writings of another.

I declare that the thesis describes original work that has not previously been presented for the award of any other degree of any institution.

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Abstract

China is the largest energy consumer in the world, and the biggest source of energy demand in China is the building sector, which accounts for 46.5% of the country's total energy consumption and 51.3% of carbon emissions. The area with the fastest growth in building energy demand in the country is the central southern hot summer - cold winter climate region.

The Passivhaus standard (and its retrofit equivalent EnerPHit) focusses on achieving ultra-low operational energy consumption. However, examples of Passivhaus and EnerPHit buildings are rare for hot climates, and this particularly true for China. When improving the energy performance of an existing building, it is also important to consider the environmental impact of any retrofit building materials that are used as part of an EnerPHit retrofitting programme. Therefore, this study investigated the energy savings, carbon emission reductions and cost savings that might accrue from retrofitting, to the EnerPHit standard, a case study dwelling located in China's hot summer - cold winter climate region.

External weather and indoor thermal conditions of the case building were monitored for 12 months, and these data were used to validate a digital model of the dwelling. The model was used to evaluate retrofitting to the EnerPHit standard, which gave energy savings of 90.1% for heating and 72.6% for cooling compared with the pre-retrofit condition. Next, different combinations of retrofitting measures were evaluated for four different build scenarios to find how the EnerPHit criteria could be met using fewer building materials. Lastly, the finalized retrofitting plans for the case building were evaluated from the carbon and cost points of view, through detailed life cycle carbon and cost assessments. The results showed that the carbon payback time of the proposed retrofitting plans was much faster than the cost payback time, and that at the end of the evaluated lifespan, savings of up to 83.4% of the carbon emissions and 18% of the costs could be achieved.

Acknowledgement

This PhD journey has been a valuable and enriching experience for my life, and I must thank the people who have helped and supported me to make this journey.

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Chapter 1. Introduction

1.1. Overview

Improving the energy efficiency of buildings is a potential way to mitigate climate change because the building sector has been a major energy consumer and contributor to greenhouse gas emissions. The International Energy Agency (2019) stated that buildings, together with the construction industry, consume about 36% of global energy production and are responsible for approximately 39% of global carbon emissions (IEA, 2019a). Therefore, the green shift to greater energy efficiency in the building sector should be a necessary and unavoidable responsibility of global governments.

China is the biggest energy consumer in the world, and is responsible for about 24% of the world's primary energy consumption (BP Energy Outlook, 2020). The building sector accounts for 46.5% of the yearly national energy consumption and is responsible for around 51.3% of national carbon emissions (CABEE, 2020). This suggests that changes in the building sector are particularly urgent for China. However, it is also challenging, since China is still undergoing urbanisation, and with the increasing requirement of thermal comfort, the building operational energy consumption has been experiencing a rapid growth for many areas.

It is essential for new buildings to be built with a high level of energy performance since this will affect the energy consumption in the following years. In China's context, although the new construction area is expanding every year (i.e. an additional 380 million square metres of new-built construction in 2020), the existing building stock had reached 67.1 billion square metres by 2018 (National Bureau of Statistics, 2021). More than 90% of these existing buildings have poor energy performance, including many of those that were built in recent years (M. Li, Zhao, & Zhu, 2013; Lin et al, , 2020). Their inadequate energy performance has placed tremendous pressures on energy resource conservation so that retrofitting these existing buildings to improve their energy performance is a solution to moderate this pressure and make efforts towards more sustainable building development (G. Liu, Li, Tan, & Zhang, 2020).

1.2. Research background

1.2.1. Research problem

Research relating to building energy efficiency, especially energy retrofitting of the existing building stock in China, has been receiving increased attention in recent years. However, a large proportion of these studies focused on the buildings in northern China, due to the more extreme weather conditions of this region compared to other parts of China (C. Chang et al, 2018). However, heating and the cooling energy consumption is increasing in many other parts of China due to the uncomfortable climate conditions (CABEE, 2016b). The hot summer cold - winter climate zone, located in the central-southern part of China, experiences weather conditions for which the mean outdoor temperature is usually between 25-30 ºC in summer and 0-10 ºC in winter, and the relative humidity level is usually between 70% and 80% all year round (Gui et al, 2018). Naturally, the thermal comfort is considered as quite poor, and a hot and humid summer together with clammy cold winter is a common thermal feeling in this climate type. However, this climate region is home to about 40% of China's population and is responsible for around 45% of the total building-related energy consumption (Gui et al., 2018; NBS, 2017). The methods used to address the uncomfortable weather condition in this climate region are air conditioning systems that supply both heating and cooling, assisted by electric heaters and fans (S. Chen et al, 2011).

Although this climate has a cold winter, the use of a hot water central heating system, or the idea of warming up the entire interior space, was historically not considered in the residential planning by the Chinese government, because the winter period and extreme level of the cold was comparatively shorter and weaker than the cold climates in the northern part of the country. It was considered costly to develop and maintain the central heating system while it would only be in operation for a short period of a year, and deal with half of the climate challenge of this climate type (Fu & Fan, 2013). Moreover, the way that the central heating system historically worked in China was by burning coal, and the harmful gases generated from this process when emitted into the very humid air of the hot summer – cold winter climate region presented a risk of causing health problems. Instead, the air conditioning system that supplies both heating and cooling meets the double requirement of this climate, and has become the main method of maintaining the entire indoor space and therefore largely improving the indoor thermal comfort in this climate region. One initial reason that the air conditioning system became popular in this climate region was that it is able to condition the indoor air temperature quite quickly– one system is designed to work efficiently for only one room and the size of the system is according to the size of the room (Z. Li & Jiang, 2009). Therefore the temperature selected by the occupants in order to match their comfort feeling could be achieved very soon under hot summers and cold winters. Moreover, the installing process for air conditioning systems is comparatively earlier than many other systems, as fewer devices and piping works are needed. The air conditioning system was only used when the thermal feeling was very poor, because it is energy intensive compared with other historical heating and cooling methods such as electric fans, burning charcoal and passive ways, but it is nowadays used much more frequently and for longer period currently due to the increasing importance of thermal comfort to residents.

As a result, the energy consumed by active heating and cooling in this climate region increased by eight times from 2001 to 2015 (CABEE, 2016b). there are also other reasons for this, such as population growth and urbanisation Therefore, improving the energy efficiency of the residential buildings in this climate region is a significant task for building energy conservation in China.

However, the first national building regulation for improving the building energy efficiency for this climate region was not published until 2001, aiming to achieve 50% energy reduction in new buildings compared with the existing building energy performance (MOHURD, 2001). This regulation was renewed in 2010 and aimed to achieve 65% energy savings in new buildings (MOHURD, 2010b). Until now, this version has been in application, but a more recent version is planned and may be published in 2021 (MOHURD, 2020). In addition, the local government of Hunan province has published more building energy saving related regulations because the local government develops regulations and codes from a more detailed basis that correspond with the national regulations. The most important and mandatory regulation for residential building was published in 2004 and renewed in 2017 (MOHURD, 2017a). However, it was not strictly enforced in the beginning, and further policies were issued, which aimed to achieve that at least 15% of new buildings meet with the local mandatory regulation in 2011, and this percentage was improved to 65% in 2016 (HUNAN.GOV.CN, 2012, 2017). The local government has also issued a few technical guidelines and codes in the recent decade to achieve the aims and improve the development in building energy saving (HUNAN.GOV.CN, 2009, 2020).

In general, the current national and local building regulations are both focused much more on urban dwellings than non-urban dwellings (Baldwin, Loveday, Li, Murray, & Yu, 2018). This could be because of the fast urbanisation in China, where the size of cities is expanding and the amount of urban residential buildings, which are mostly high-rise flats buildings that accommodate many populations, has been increasing dramatically in recent several decades. Also, the residents in China account for around 54% of the total population, and they mostly live in those mass developed high-rise buildings, where energy retrofit could be applied as part of large-scale refurbishment programmes. On the non-urban side, however, far fewer real estate companies are involved in constructing more residential buildings. The residential buildings in non-urban areas such as suburbs, towns and villages are usually low and medium-rise buildings that would usually be occupied by a single-family (though the family could be a large one that includes several generations). Those buildings have also been largely renewed in the past decades, because the old ones are poorly constructed, and there might even be a safety risk.

Moreover, the extent of the residential areas in non-urban regions has also increased with the renewing process, but there is still overall much less density than the urban area, and those renewed buildings will usually have been built by the local construction team that hired by the house owners directly. Furthermore, the difference in total building floor area between the existing urban and non-urban living areas in China is minimal, being 259.7 and 245 billion m^2 respectively, and the energy consumption of non-urban dwellings in China accounts for about 23% of the total building sector (CABEE, 2016). Thus, retrofitting the non-urban dwellings is crucial for the energy transformation of the building sector.

With the country's rapid development, many of the traditional dwellings within China’s suburban towns and villages in the hot summer - cold winter climate region have been replaced by reinforced concrete structured buildings in the last several decades (Luo et al, 2021). Those buildings were usually designed and built based on the owners' desire and construction teams' experiences, instead of following this climate region's energy efficiency design guidelines. The energy performance of these residential buildings was considered as poor, as no energy-efficient measures were applied, but they are structurally sound and were intended to last for many years. Along with improving thermal comfort requirements for occupants, the energy consumption from non-urban dwellings is expected to increase in the following years. Therefore, they have a great potential for energy savings from high standard energy retrofitting.

The German Passivhaus EnerPHit standard (PHI, 2016) exemplifies a very rigorous retrofit approach that aims to achieve significant energy savings without impairing indoor thermal comfort during building operation. The performance of Passivhaus has been widely proven over the world, and there are successful Passivhaus applications in China. However, the Chinese government does not currently adopt the Passivhaus standard or similar ultra-low energy building regulation as the mandatory standard for new builds or retrofits, which is currently the same for most countries worldwide. The current mandatory regulations in China have much lower energy efficiency requirements than the Passivhaus standard, but those Chinese regulations have been updating, with higher energy saving targets. Continuously retrofitting the existing residential buildings to meet the changing regulations should not be considered as a suitable solution. Currently, the retrofitting rate is low in China, with only 2% of the urban residential building stock in the hot summer - cold winter climate region retrofitted towards the current building regulation during five years between 2010 and

2015 (MOHURD, 2017b). Retrofitting the rest of the existing dwelling stock towards a high energy efficient standard, such as the Passivhaus EnerPHit standard, should be a long-term and much more sustainable solution that could be leading to significant energy savings in building's lifetime without the need for multiple retrofits.

Many studies have been carried out relating to the Passivhaus standard, such as research in energy performance under different climate conditions, indoor environment and experience, and life cycle assessment. However, there is still a doubt about the Passivhaus performance under hot climates, since most of the achievements of the Passivhaus standard were demonstrated under the cold European climates (Badescu, Laaser, & Crutescu, 2010; Figueiredo, Figueira, Vicente, & Maio, 2016). Also, the high amount of material requirement and monetary investment for achieving the Passivhaus standard has been given increasing attention. Accordingly, life cycle assessments of environmental impacts and cost paybacks have become a further topic of Passivhaus research (Fokaides, Christoforou, Ilic, & Papadopoulos, 2016). There are much fewer studies on Passivhaus buildings and the standard in China's context than those for European climates. Current studies focused on demonstrating Passivhaus projects in northern China’s climate region (Lin, Zhao, Yang, Hao, & Li, 2021). Therefore, a more diverse selection of case studies under different climate regions in China is required to demonstrate the full range of Passivhaus performance for China's various climatic regions.

1.2.2. The focus of this research

The existing suburban dwelling stock in the hot summer - cold winter climate region of China is expected to consume increasingly more energy in active heating and cooling in order to cope with the more extreme climate. The energy retrofitting of these buildings is a significant part of a green building intervention, but less attention has been paid to them than the dwellings in northern colder regions and urban regions in China. Thus, this research considers the strict Passivhaus EnerPHit standard as a retrofitting solution for suburban dwellings under this climate region in order to achieve a significant energy saving in active heating and cooling. A typical suburban residential building located in Huilong town, Hunan province, was adopted as the case study for this research. The retrofitting process, which followed the Passivhaus EnerPHit concept, was applied virtually and evaluated through dynamic simulations, and the performance of the retrofitted case building was analysed in terms of energy saving, life cycle environmental impact and cost paybacks.

1.3. Research questions

In order to achieve the aims of this research, the following research questions were addressed:

1. What are the retrofitting measures that enable the chosen case building to meet the criteria of the EnerPHit standard?
2. How much energy saving could be achieved by implementing EnerPHit compared with the existing situation?
3. Is it possible to decrease the amount of retrofitting material inputs while still achieving the EnerPHit standard?
4. Is the proposed retrofitting plan still profitable in terms of both environmental impact and the monetary investment, compared with the pre-retrofit situation, when a long building lifespan is considered?

1.4. Research aim and objectives

For achieving the research aims and answer the proposed research questions, the following objectives will be studied:

1. To investigate the thermal and energy performance of a Hunan case building and set up a baseline model for the analysis of various retrofit measures.
2. To investigate the energy performance improvements from the retrofitting measures that obey the Passivhaus concept and identify a step-by-step retrofitting process that enables the case building to achieve the EnerPHit standard.
3. To evaluate the possibility of minimising the retrofitting inputs while still achieving the EnerPHit standard energy performance.
4. To evaluate the environmental impact and cost performance of the proposed retrofitting solutions through a detailed life cycle carbon and cost assessment.

1.5. General methodology

The primary evaluation of this research is whether achieving the Passivhaus criteria is an appropriate retrofitting solution for the targeted dwellings and climate type. The research process is substantially addressed in four linked stages in order to answer the proposed research questions. The research process is demonstrated in Figure 1-1, and each research stage aims to answer one of the research questions by accomplishing a part of the research objectives.

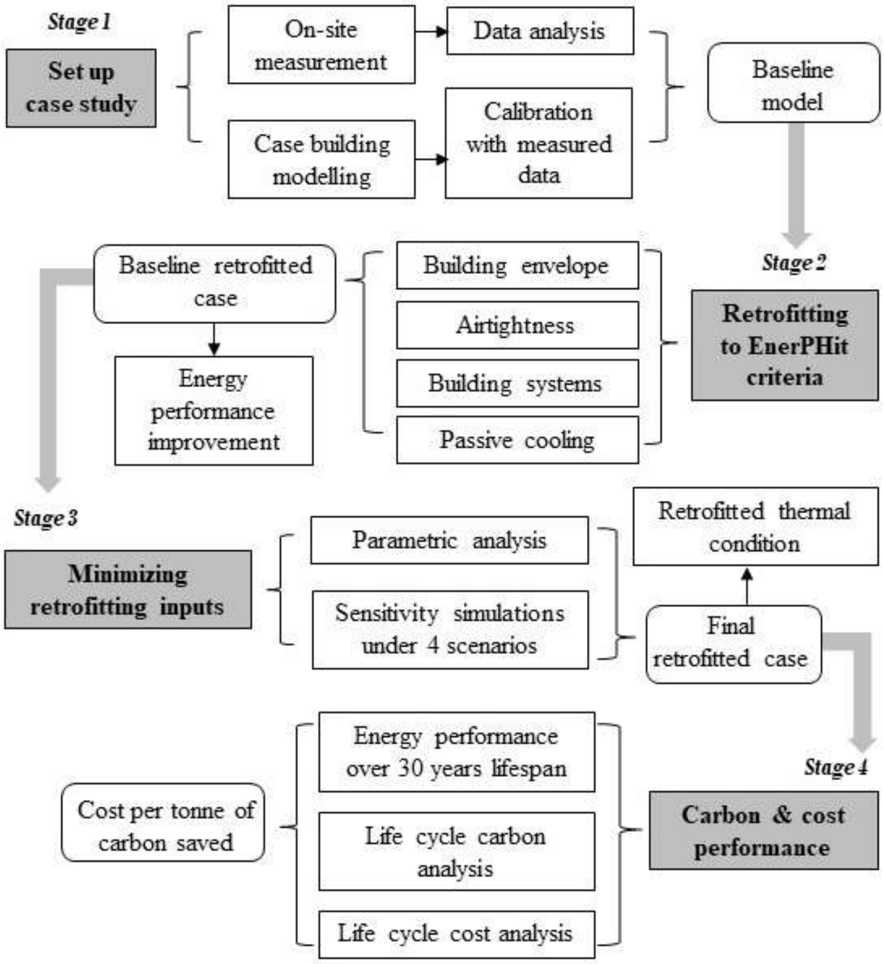


Figure 1-1, General research methodology demonstrated by the research stages.

1.5.1. Stage one - setting up a case study

In this stage, a suburban residential building in Hunan province, located in a hot summer - cold winter climate, was selected as the case building for this research. Hydrothermal data were collected for more than one year from both inside and outside of the building, including data about air temperature, relative humidity, and indoor CO_2 levels. The main research progress in this stage is described below:

- **Analysis of the recorded data**: environmental data logging was arranged and analysed in detail to understand the local weather characteristics and indoor thermal conditions. The indoor thermal comfort of the case building was then evaluated through an adaptive model.

- **Modelling**: the dynamic thermal simulation software DesignBuilder was used to build a model of the case building based on its physical features.

- **Calibration**: The recorded hydrothermal data were adopted to calibrate the model, and after a three-stage calibration process, the model became the baseline model that was ready for the retrofitting simulations. The energy performance under the pre-retrofit condition was analysed based on the baseline model.

1.5.2. Stage two - retrofitting towards the EnerPHit criteria

The second stage involved evaluating each of the retrofitting measures that followed the Passivhaus concept, using the calibrated baseline model as a base, and then proposing a retrofitting plan that enabled the case building to achieve the Passivhaus EnerPHit criteria. The main research progress in this stage could be described:

- **DesignBuilder simulation of the step-by-step retrofitting process**: the retrofitting measures were virtually applied to the baseline model, and the performance was analysed through the DesignBuilder simulations until the EnerPHit energy criteria could be achieved. The energy-saving from the retrofitting was analysed following the measures applied step-by-step.

- **PHPP analysis**: the retrofitting solution proposed for the case building through the analyses of DesignBuilder simulations was modelled in Passive House Planning Package (PHPP), which is the Passivhaus certification tool to makes sure that the solutions will meet the Passivhaus EnerPHit standard.

1.5.3. Stage three - minimising the retrofitting inputs

The retrofitted results in stage two suggested an energy performance that actually surpassed the standard required, which motivated the research objective in stage three.

The possibility of reducing the retrofitting inputs, whilst still meeting the standard required energy efficiency, was evaluated through parametric analyses and sensitivity simulations, using the retrofitted model in stage two as a baseline retrofitted case. The progress in this stage is described below:

- **Parametric analysis**: a series of parametric analyses about the envelope insulation, glazing, and airtightness were applied to figure out the possibility of reducing the inputs for each of the retrofitting measures.
- **Final retrofitting plans**: four scenarios of retrofitting measures were hypothesised, and the final retrofitting plan, which required the lowest amount of retrofitting inputs, was determined through sensitivity simulations of combinations of different measures under each scenario.
- **Thermal condition evaluation**: the indoor thermal condition of the retrofitted case was compared with the condition of the pre-retrofit case and evaluated against the Predicted Mean Vote (PMV) thermal comfort model and Passivhaus requirements.

1.5.4. Stage four - life cycle assessment

In stage four, the retrofitting plans proposed for the case building were evaluated from the carbon and cost points of view, and a detailed life cycle carbon and cost assessment was conducted for a 30 years building lifespan. Together with the energy performance analyses carried out in previous stages, the Passivhaus standard retrofitting was comprehensively evaluated to achieve the initial research aim. The progress in this stage is described below:

- **Future energy performance**: the energy performance of both pre-retrofit and retrofitted case were simulated by DesignBuilder with future weather files.

- **Life cycle carbon analysis**: embodied carbon and transport carbon of the retrofitting measures were collected and, together with the operational carbon in 30 years, the life cycle carbon footprint of both pre-retrofit and retrofitted cases were calculated and analysed against each other.

- **Life cycle cost analysis**: to compare the life cycle cost differences of the pre-retrofit and retrofitted cases. Because the cost of energy would change over time, an electricity price prediction analysis was included in this analysis.

- **Cost of carbon reduction**: the ratio between the cost of the retrofitting and the carbon reduction from it was evaluated as a performance indicator, in order to analyse the combined impact of both carbon and cost. This impact was analysed for both the proposed retrofitting plans and the individual retrofitting measures.

1.6. Contributions to knowledge

This thesis is composed of original research about the performance evaluation of the Passivhaus EnerPHit retrofitting of suburban dwellings in a hot summer - cold winter climate. The main contribution from this thesis is that an exhaustive analysis of the retrofitting process and results from three essential aspects in building performance (energy, carbon and cost) were carried out through a case study analysis, so that the efficiency of the Passivhaus standard retrofitting was revealed from a comprehensive perspective. This research used a detailed case study to fill the Passivhaus EnerPHit research gap under a challenging climate type, which should be a valuable reference for other researchers. Finally, the different stages of this research have been published and presented in several academic journals and international conferences.

1.7. Thesis structure

This thesis has been structured into seven chapters, and an outline for each chapter is given below:

Chapter 1 introduces the necessity of energy retrofitting of existing suburban dwellings in the hot summer - cold winter climate region of China, as this is a significant component towards the energy conservation of the Chinese building sector. It also highlights the great potential of energy saving through retrofitting follow the Passivhaus EnerPHit standard, and accordingly, the research aims and objectives are developed. A general methodology of this research is also illustrated in this chapter.

Chapter 2 presents a literature review about retrofitting measures in China, the characteristics of the studied climate and the existing residential building situations in Hunan province. When compared to the current retrofitting regulations, the EnerPHit standard is recognised to have great energy saving potential. Then, the experiences from Passivhaus studies and existing Passivhaus projects were examined, with a particular focus on China, to establish an overall retrofitting vision for Hunan housing.

Chapter 3 introduces the case building of this research, a four-story suburban dwelling in Hunan province. The on-site monitored data were organised and analysed to demonstrate the indoor thermal conditions of this building. Then, a baseline model was created and calibrated using the monitored data, and from then, the energy performance of the pre-retrofit case was analysed.

Chapter 4 presents a detailed step-by-step retrofitting process which followed the Passivhaus concept, in which each retrofitting step and the level of the measures were simulated using DesignBuilder, and the subsequent energy savings from each measure were illustrated. In the end, a retrofitting plan which enabled the case building to meet the EnerPHit criteria was established, and this retrofitting plan was also examined by PHPP and compared with the DesignBuilder results.

Chapter 5 is developed from Chapter 4, in which the retrofitted results suggested that the retrofitting plan could be improved. Thus, this chapter developed a methodology including parameter analysis and sensitivity simulation for improving the retrofitting plan to decrease the retrofitting material inputs while still achieving the EnerPHit standard energy efficiency. The indoor thermal condition after the retrofit were also analysed and compared with the pre-retrofit conditions.

Chapter 6 examines the carbon and cost performance of the proposed retrofitting plan. The energy performance of the case building over a 30 years lifespan was simulated with future weather files. Then, a detailed life cycle carbon and cost assessment was carried out for which, together with the analysis of cost per tonne of carbon saved (CTS) and the previous chapters, a comprehensive analysis of Passivhaus EnerPHit standard retrofitting was completed.

Chapter 7 concludes the thesis by summarising the main work and key findings from this research. The research questions are answered, the limitations of the study are considered, and further research objectives are suggested.

Chapter 2. Literature review

2.1. Overview

Energy retrofitting of existing housing has been recognised as a method with great potential for sustainable interventions in the building sector in order to respond to climate change and resource depletion. China is expected to take an increasing interest in building energy retrofitting because there is a large existing housing stock in China, and the majority of its stock was built with basic materials and construction techniques. Furthermore, residential energy consumption has been increasing due to higher thermal comfort demands from occupants. How to efficiently reduce the energy consumption, whilst keeping a good indoor thermal comfort in the existing housing, is an important topic. This research focuses on some possible solutions within the context of one of China's climate zones, the hot summer - cold winter climate region, more specifically, existing housing in Hunan province, which is located in this region. Therefore, the purposes of this chapter were to review (i) general retrofitting experiences in China, (ii) the characteristics of the targeted climate type and Hunan's housing situation, (iii) a method with high energy saving potential, the Passivhaus retrofitting standard, and (iv) the performance of existing projects and studies, to establish an overall retrofitting strategy for Hunan housing.

2.2. Building retrofitting

2.2.1. Why retrofit?

Climate change is one of the most significant current challenges that causes serious environmental problems in many ways for both humans and nature, such as global warming, more frequent extreme weather events and rising sea levels (*IPCC*, 2014). Greenhouse gas emissions are thought to be responsible for the climate change, and a large proportion of emissions result from the energy production and consumption of human activities (Höök & Tang, 2013). At the same time, the increasing energy demand in active cooling, partly due to increases in climatic temperature around the world, is increasing the vicious circle of climate warming. Therefore, reducing greenhouse gas emissions is a primary driver for sustainable development in the built environment, and retrofitting of existing buildings for improving their energy efficiency is an essential part of this effort, as a large proportion of the housing stock worldwide is older buildings with poor energy performance (G. Ma, Liu, & Shang, 2021).

Another reason for updating the energy efficiency of existing buildings is the conflict between natural resources exhaustion and the increasing requirements for thermal comfort indoor environments from residents. Although there have been significant developments in clean energy production in recent years, 38% of the world's electricity production (ten thousand TWh) was still generated from coal in 2018 (IEA, 2019b). The percentage of electricity generated by renewable sources is projected to increase, along with an increase in total electricity production. However, a slightly greater amount of electricity is still expected to be produced by coal in 2040 under the current policy scenario (IEA, 2019c). Thus, the amount of greenhouse gas emission from electricity production (the main energy source used in buildings) is expected to be continuously increasing in the next few decades. Energy efficiency improvements in buildings are very important under this context as it is a sustainable solution with great potential to abate global greenhouse gas emissions (Pacheco-Torgal, 2017).

In many countries the size of the existing building stock is high, proportionally, compared to the number of new buildings. Thus, prioritising retrofitting existing buildings to a higher performance standard is a crucial step towards overall sustainability in the building sector (Si & Marjanovic-Halburd, 2018). Although China is still undergoing rapid urbanisation, and its annual new construction had experienced rapid growth, this trend has shown a slowdown in recent years, as shown in Figure 2-1. Most recently, the yearly growth rate was lowered to 5.6% in 2020 against the total existing stock of 67.1 billion square metres in 2018 *(*National Bureau of Statistics*,* 2021*)*. However, the current building stock in China still represents the majority, and most of the existing structures are high energy consumption buildings as they were built with basic materials and no insulation applied. Moreover, many of the new buildings which have been built in recent decades have not managed to achieve the local standards. For example, only about 20% of the new buildings in Hunan province between 2011 and 2015 have fulfilled the requirement of the mandatory standard for energy saving (HUNAN.GOV.CN, 2017). Moreover, the current Chinese mandatory standards are already have lower requirements than many international standards (Zhou, Levine, & Price, 2010). Therefore, retrofitting the existing building stock is an inevitable way forward for sustainable building development in China.

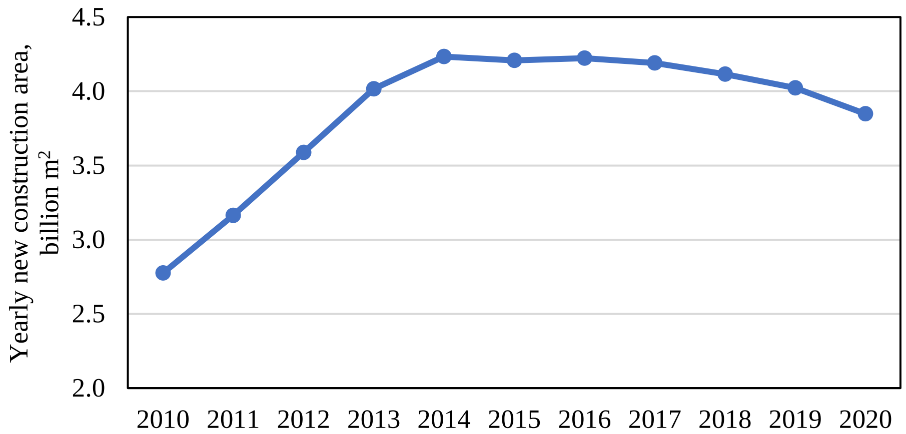


Figure 2-1: Change of yearly new construction areas in the past ten years in China (National Bureau of Statistics, 2021).

In addition, there are other reasons driving the retrofitting of the existing building stock, such as the increasing expectations of quality of life for residents. Existing buildings are usually poorly insulated and unable to retain the indoor heat efficiently, and envelope retrofitting is supposed to help decrease the energy consumption for heating and cooling in buildings (B. Li, Du, Yao, Yu, & Costanzo, 2018). Building retrofitting could also help improve indoor air quality, which is a significant problem in China, especially in the northern part of the country (Ecns.cn, 2017). Moreover, retrofitting could improve a building’s function and lifespan and significantly reduce maintenance work and costs during the building's operational lifetime (Gorse et al., 2015).

2.2.2. Retrofitting measures

According to a review by He and Wang (2021) of energy-efficient and low-carbon transition-related measures from retrofitting experiences in China, the overall retrofitting measures can be grouped into three main categories by different methods of reducing environmental impact from buildings (He, Hossain, Ng, & Augenbroe, 2021a; Y. Wang et al., 2020). As shown in Figure 2-2, achieving energy conservation, energy generation and energy management in buildings are the three main methods for reducing building impact, and retrofitting measures could be categorised by these three purposes.

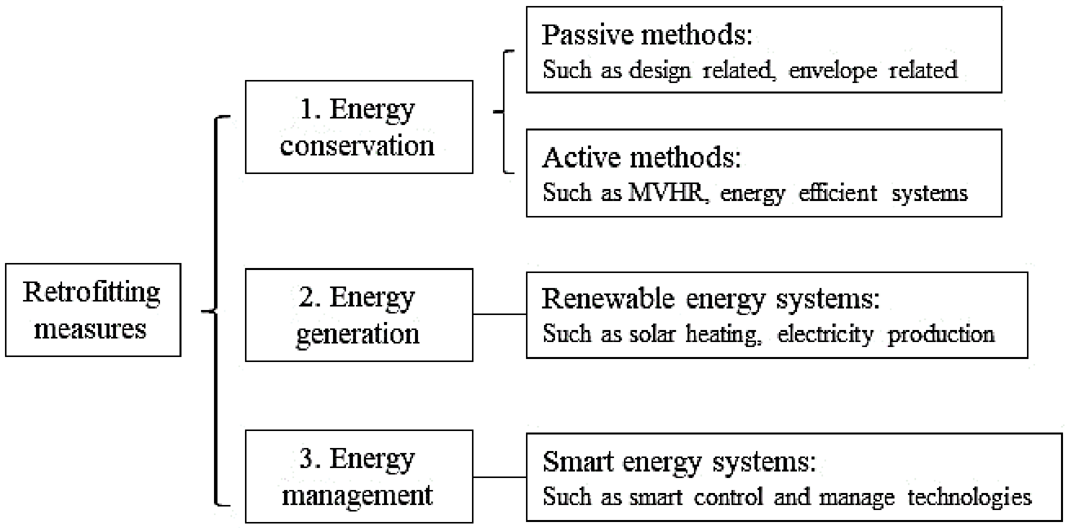


Figure 2-2: Retrofitting measures categorised by purposes (He et al., 2021a; Y. Wang et al., 2020).

Energy conservation-related passive measures

Among all the different retrofitting measures, those related to reducing the energy demand and consumption in buildings should be the most essential measures because they directly reduce greenhouse gas emissions. The energy conservation-related measures could be categorised into two aspects of passive and active measures. The passive measures are climate and location related, and each building deserves individual analysis when deciding the suitable passive measures (X. Zhao, Tan, Shen, Zhang, & Wang, 2019). Building geometric design, such as building shape, orientation and window size, are significant to a building's energy performance because they significantly affect the solar gain from the sun, natural ventilation efficiency and natural lighting in buildings (Gan et al., 2019; Jalal & Bani, 2017; Xue, Li, Xie, Zhao, & Liu, 2019). However, in retrofitting projects, it could be quite challenging to improve those geometric features because of the physical limitations of the existing structure (Gorse et al., 2015). Instead, passive heating and cooling methods, that assist with solar heat gain in winter and avoid excessive heat gain and overheating in summer, are significant approaches in building retrofitting. With those passive measures, it is possible that the active heating and cooling energy consumption can be decreased (Chan, Riffat, & Zhu, 2010).

Passive measures for improving the envelope performance usually involve insulating the exterior walls, roof, ground floor, and utilising the better thermal performance of windows, which all promote an enclosure that significantly decreases the thermal heat transfer between the indoor and outdoor environment so that more stable and comfortable indoor thermal conditions can be maintained and the energy demand of the conditioning system is decreased (Aditya et al., 2017). Insulating the building envelope has been considered as an efficient method in cold climates and helps with reducing the cooling demand in places with hot climates. The thermal insulation layer could separate the indoor conditioned air from the high outdoor temperature and reduce cooling energy dissipation. Effective design is required as insufficient amounts of insulation may lead to a higher cooling energy demand, while a very thick insulation layer does not, leading to a better cooling energy conservation (Bojic, Yik, & Leung, 2002). Airtightness is another factor that influences the envelope performance. It is a measure of the amount of intended (ventilation) or unplanned (infiltration) airflow between an enclosure and the outdoor environment. The poorer the airtightness performance is, the more the thermal (heating or cooling) demand is increased (Fine, Gray, Tian, & Touchie, 2020).

Energy conservation related active measures

Energy conservation related to active measures are used to improve the efficiency of energy use in buildings so that the total consumed energy amount can be decreased. Standard measures include improving the energy efficiency of heating and cooling systems, adopting heat recovery systems, improving lighting efficiency and the efficiency of other assistive applications (Y. Wang et al., 2020). For example, low energy efficiency boilers could be replaced with modern high energy efficiency boilers, thereby saving energy for the same activity (He, Hossain, Ng, & Augenbroe, 2021b). A mechanical ventilation system with heat recovery (MVHR) function can be adopted in deep retrofitting, such as buildings targeted with the EnerPHit standard or low/zero energy buildings. However, a well-insulated envelope with a very low air infiltration rate is usually required as a foundation for a MVHR system to achieve its designed efficiency in operation (Crawley, Wingfield, & Elwell, 2019). Replacing traditional lighting with LED (light-emitting diode) lighting is another energy-efficient step, as the energy efficacy of a LED lamp is about 150 to 200 lm/W, while that of a traditional type of compact fluorescent lamps is about 50 to 100 lm/W. However, the price of LED lighting is about three times higher than traditional lighting in many parts of China (Akil, Mawar, Mangngenre, & Amar, 2020; He et al., 2021b).

Energy generation related measures

Renewable energy measures are commonly incorporated with building retrofit, especially when aiming to achieve a low or zero carbon energy target in operation such that the consumed energy could be counterbalanced by the renewable energy generated. The most used renewable sources in China include solar hot water, solar photovoltaic, wind power and hydroelectric (Z. Ma, Cooper, Daly, & Ledo, 2012a). However, rural residential buildings usually have a greater potential for adopting renewable energy technologies than urban residential buildings because essential factors, such as site access, neighbouring surroundings and building function, are required for the installation of many kinds of renewable energy technologies, while those conditions are usually lacking in high-rise residential buildings in densely populated urban areas (He et al., 2021b).

Energy management related measures

Energy management-related measures are technologies capable of smart monitoring, managing and controlling the building systems and applications to reduce energy consumption in buildings (Y. Wang et al., 2020). Sensor control for lighting is a relatively advanced technology that allows lighting energy consumption reduction while providing lighting comfort to residents (Zou et al., 2018). Wireless technologies linked with smartphones give occupants a more convenient way to manage household devices and applications (Silva, Khan, & Han, 2018). Moreover, the development of big data and data management, research and development about data analysis, decision making and event management is a possible means to provide better efficiency in energy usage in the future (Silva, Khan, & Han, 2017).

2.2.3. Retrofitting outcomes

In general, energy-saving and environmental impact reductions during the operational period are the most direct outcomes from building energy retrofitting. Additionally, a high standard of occupant comfort is expected from retrofit (Jagarajan et al., 2017). However, many factors need to be considered for achieving a significant retrofitting result, such as climate characteristics, existing building conditions and retrofitting budgets. Therefore, according to the specific context of each building, a combined adoption of a selection of retrofitting measures are usually required for boosting the retrofitting outcome by the thermodynamic performance and physical interactions between the different measures (Gorse et al., 2015). Many multi-objective retrofitting studies have looked at optimal retrofit strategies. Some examples of recent comprehensive reviews on this can be found in (S. Chang, Castro-Lacouture, & Yamagata, 2020; Costa-Carrapiço, Raslan, & González, 2020). In addition, the building regulations or assessment criteria that the retrofit seeks to achieve are directly correlated with the outcome in energy savings and greenhouse gas reductions after retrofit is completed (Z. Ma, Cooper, Daly, & Ledo, 2012b). Thus, for mitigating current climate change, the appropriate selection of retrofit targets is essential for the global environment.

2.2.4. Evaluating building retrofits – life cycle analysis

As good energy performance is the key aim to a building retrofit activity, it is thus also an important factor in evaluating the retrofitted outcome. However, retrofit is a complex system in which many other factors should be considered, such as capital investment, comfort, technology, ecology and other aspects (Asadi, Silva, Antunes, Dias, & Glicksman, 2014). A multi-objective analysis allows optimal retrofitting solutions to be found from the trade-offs between two or more important aspects, such as the trade-off between energy saving and retrofit cost (Carlucci, Cattarin, Causone, & Pagliano, 2015). However, the time period is actually a significant factor, especially in deep retrofits, as the retrofitted building is supposed to operate for many more years. As such, a considerable uncertainty could appear to the initial evaluated results, as many important factors, such as energy consumption and carbon emissions, could accumulate over the lifetime of the building (Gorse et al., 2015). Life cycle analysis (LCA) is an advanced technique that assesses the entire investments and paybacks over a considered time period, to evaluate retrofit results over the long term (B. Wang, Xia, & Zhang, 2014). The benefit of life cycle analysis is that it allows many factors to be involved in its evaluation boundary, and it assesses the retrofitted results according to the relative effectiveness and robustness of the retrofitting measures over different time scales rather than a stabilised performance (Nik, Mata, & Sasic Kalagasidis, 2015).

Overall, life cycle assessment involves all activities, such as the manufacturing process of building materials and products, transportation, distribution, use, maintenance, disposal and recycling that occur in a building's entire lifetime (Chau, Leung, & Ng, 2015). According to different perspectives when evaluating the environmental impacts of buildings, life cycle studies can be classified into three main streams: life cycle energy, carbon footprint, and costs assessments (Chau et al., 2015; K. Lu, Jiang, Yu, Tam, & Skitmore, 2021).

2.3. Retrofit under a hot summer - cold winter climate

2.3.1. The hot summer and cold winter climate

Adaptation to climate is one of the most critical principles for low-energy buildings. Therefore, it is required to understand the characteristics of the targeted climate before any building energy saving retrofit strategy is undertaken. Among the existing residential buildings in China, those in the hot summer - cold winter zone have the dual demand of space heating and cooling, and so are undoubtedly significant energy consumers. This climate type covers a large area of central and southern China, which involves 14 of its 22 provinces according to the Chinese Ministry of Housing and Urban-Rural Development (MOHURD, 2017c), as shown in Figure 2-3. The main indicator that (MOHURD, 1993) identified for this climate regionalisation was based on the outdoor monthly mean temperature in January (the coldest month) and July (the hottest month), which should be within the ranges of 0 – 10ºC and 25 - 30ºC respectively. Another significant characteristic of this climate region is the high relative humidity level, with the yearly mean value usually around 70 – 80%. The hot summer - cold winter climate zone is a large geographical area and, therefore, incorporates differences in local climates. For example, the eastern region faces the sea and is windier in general, while the middle region has a relatively more humid summer and the west part has less solar radiation (MOHURD, 1993). However, the common features of extreme temperatures and relative humidity contribute to significant challenges in this large region in terms of buildings performing well in both thermal comfort (B. Li et al., 2010) and energy conservation (Z. Wang, Zhao, Lin, Zhu, & Ouyang, 2015).

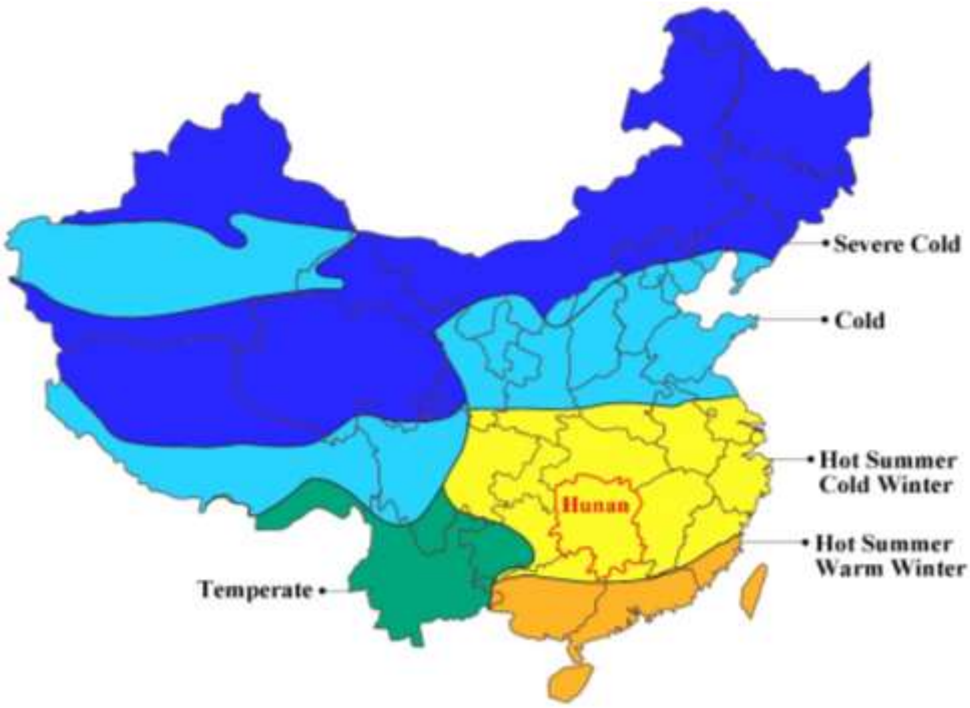


Figure 2-3: The climate regionalisation for architecture and provinces division in China， (MOHURD, 1993).

Hunan province is one where the entire area is within the hot summer - cold winter climate zone. A study (B. Li, Yu, & Li, 2011) compared eight capital cities in eight provinces in this climate area using weather data for a typical meteorological year (TMY) from the China Meteorological Administration. The results showed that for the hottest month, the capital city of Hunan province, Changsha, had the highest monthly mean temperature among the studied cities, at 29.3ºC, which is up to 1.7ºC hotter than other cities. Moreover, the number of days that Changsha’s daily mean temperature was higher than 35ºC was as many as 30 days. On the other hand, its monthly mean temperature in the coldest month was 4.6ºC, which was a medium-low value compared to the other cities. Using the same weather data source (F. Song et al., 2007), the software Climate Consultant 6.0 (SBSE, 2021) provides a detailed picture of Changsha's temperature and relative humidity in each month, as shown in Figure 2-4, where characteristics for a wet cold winter and humid hot summer weather could be viewed. Heating degree days (HDD) and cooling degree days (CDD) are common measures to represent climatic condition, and for Changsha, there are 1586 HDDs and 1243 CDDs against a calculation baseline of 18ºC. According to the Chinese code for thermal design of the civil building, the baseline for HDD is also 18 ºC, while for CDD, it is based on 26 ºC, and thereby Changsha has only 230 CDDs (MOHURD, 2017c). This shows that, although Changsha has the hottest summer conditions in the hot summer and cold winter climate, the demand for active heating in winter would still be higher than for cooling in summer. However, Changsha's heating requirement is still considered moderate compared with northern Chinese cities like Beijing (2450 HDDs) under the same baseline and that of many European countries (Atalla, Gualdi, & Lanza, 2018).

For global horizontal insolation, the energy a surface would receive at midday is around 900 W/m^2 and 450 W/m^2 in July and January respectively. In terms of the wind situation in this region, the wind direction is usually north-westerly in winter time and south-easterly in the summer time. The wind speed changes in this area are relatively small, where the highest monthly mean value is 2.4 m/s appears in December, and the lowest is 1.9 m/s in July *(*Klimaat.ca/epw*, 2021)*.

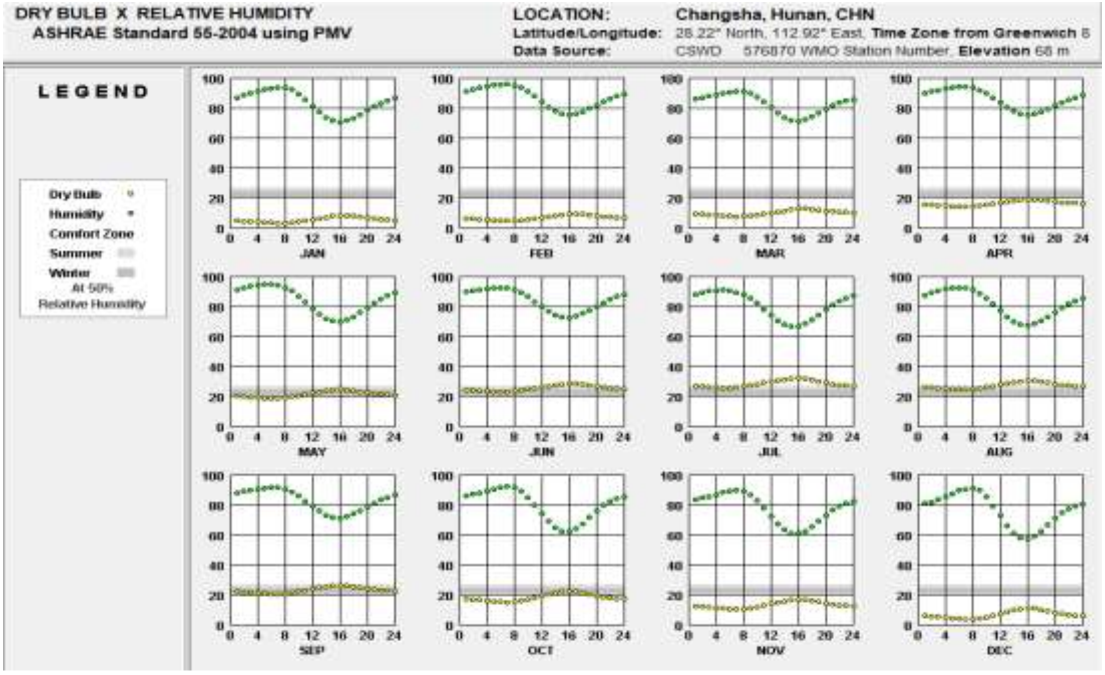


Figure 2-4: Outdoor dry bulb temperature and relative humidity illustrated by month, source from SBSE (2021).

2.3.2. Responding to the climate

Figure 2-5 displays a psychrometric chart for Changsha, which represents Hunan province. In this chart, a distribution of hourly air thermal conditions is compared against the comfort zones for dwellings in this climate region. The green and red dots represent the hours that were considered as comfortable and not comfortable, respectively. When the indoor environment was not air-conditioned (the main method of both active heating and cooling in this region), there was only 3.5% of the 8760 hours in the year within the comfort zone. However, a series of generic design strategies that could improve the thermal feeling are provided in the upper left box of the chart, which should give an approximate idea about retrofitting under this climate. The chart suggests that active heating and cooling are essential to this climate, and due to the high humidity throughout the year, active dehumidification is also considered very helpful. Internal heat gains and sun shading of windows were the most effective passive methods for this climate, with passive solar gains recommended in winter.

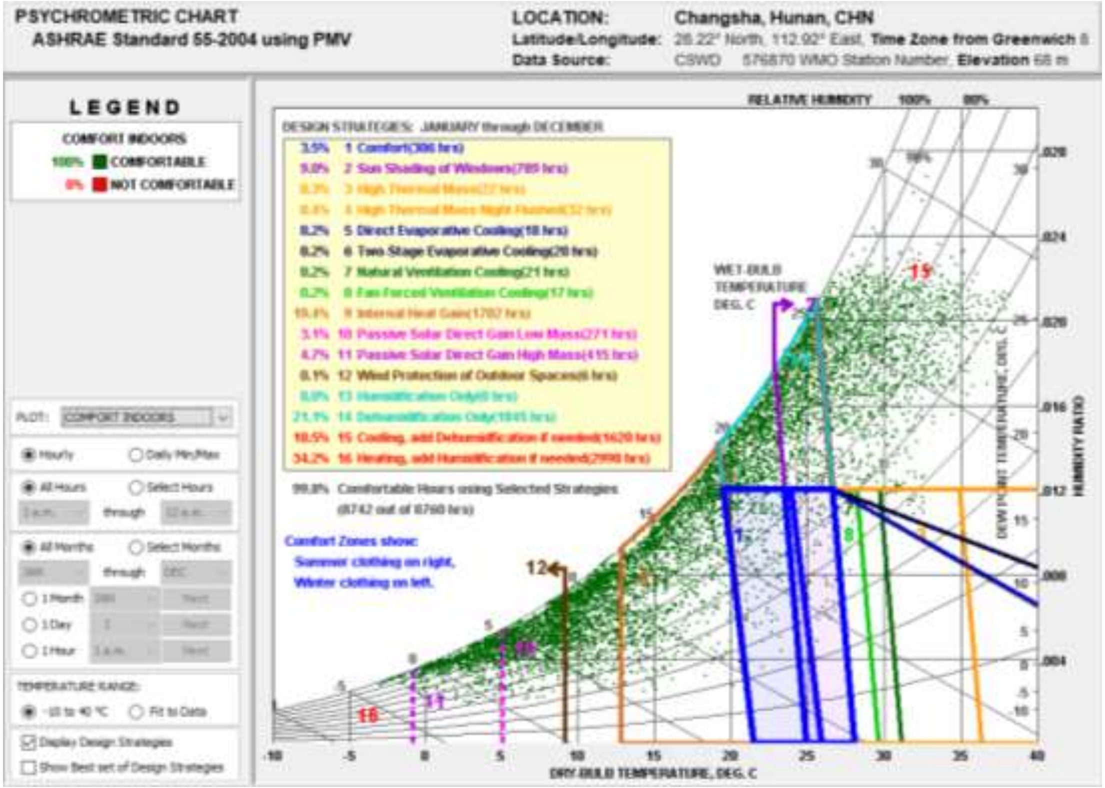


Figure 2-5: Distribution of hourly thermal situation against with thermal comfort ranges provided by different design strategies, source from SBSE (2021).

Climate conditions significantly impact on both heating and cooling energy demand and thermal comfort. Although active heating and cooling are necessary for the studied climate, reducing energy loads is still possible from adequate passive strategies (Campaniço, Hollmuller, & Soares, 2014). Based on a review of some recent studies in passive cooling and heating methods under different climate backgrounds (Bhamare, Rathod and Banerjee, 2019; Tejero-González *et al.*, 2016; Chan, Riffat and Zhu, 2010), several passive methods were found that may be relevant to the studied climate type in this research:

Passive cooling methods

For passive cooling, solar and wind control related methods are frequently utilised in the hot and humid climates. Shading is one of the most often considered passive solar cooling strategies, particularly for hot areas, and shading elements are designed in many shapes to suit the local surrounding and building geometry (Kirimtat, Koyunbaba, Chatzikonstantinou, & Sariyildiz, 2016). For example, Yu and Tian, (2008) evaluated the performance of shading methods, including (i) horizontal/vertical overhangs, (ii) four types of window inner shading and (iii) windows' outer louvre shading, on a six-floor residential building located in Changsha (capital city of Hunan province). Results showed that the outside louvre shading was the most efficient type, giving a 17.87% decrease in cooling energy consumption (Yu, Yang, & Tian, 2008). Similar research in Singapore, which experiences a hot and humid climate, showed an energy saving in the range between 2.6 - 10.1% after 0.3 - 0.9m horizontal shading devices were applied (Wong & Li, 2007), and this shading method reduces the indoor temperature by about 1ºC according to an earlier research of this scholar (Wong & Istiadji, 2003). The solar chimney is another solar cooling method, which utilises the buoyancy effect whereby hot air rises out of the top of the chimney and cool air enters the building at lower levels. This method usually requires an integration system such as a water spray system for a boost effect. However, it has been reported that this method works much less efficiently in a hot and humid climate than in a hot and dry climate (Bhamare et al., 2019). A case study in Thailand's hot and humid climate suggested that indoor temperature decreased between 2 - 6.2ºC in a wooden structure cell room that adopted a solar chimney with a dampened roof (Chungloo & Limmeechokchai, 2007). Under a very hot and dry climate, the monitored result at a Saudi Arabian library, which utilises two cooling towers that are attached with water spray, has shown an astounding passive cooling effect, as the indoor air temperature was cooled to 25.8ºC when the outdoor dry bulb temperature was 46 ºC (Alshenaifi & Sharples, 2019).

Natural ventilation is an efficient method of diminishing the heat stored inside a building. Its efficiency is influenced mainly by the air temperature difference between indoor and outdoor environments, wind velocity and direction, and relative humidity (Santamouris & Kolokotsa, 2013). For the hot summer - cold winter climate, however, this method is not highly recommended, as the indoor and outdoor temperature difference is slight in the summer period, even at night time (Givoni, 2011), but it may still be an ideal way during inter-season months (Bulut & Aktacir, 2011). A few published case studies have presented how this method works for a hot and humid climate, such as for a standard public housing block in Hong Kong, which reported an indoor temperature drop of 5ºC (Yik & Lun, 2010), while for two other cases, temperature decreases of 4ºC and 2ºC were recorded in a traditional house in India (Shanthi Priya, Sundarraja, & Radhakrishnan, 2012) and Beijing (Ji, Su, & Khan, 2012) respectively.

Radiative cooling is a method that utilises cold water as a medium on a heated surface, such as a roof during the nighttime. Thus, the stored heat inside the building could be transferred into the water, and the water then dissipates the heat to the cooler air in the nighttime. This method was reviewed by Bhamare et al. (2019) under a different type of climate, and the results suggested that its efficiency was quite high for hot and humid climates as an energy-saving ratio between 8.2% and 44% was found in the reviewed cases. However, Zhao, Liu and Jiang, (2016) highlighted that this cooling method is only appropriate for buildings with large surface area exposure to solar radiation and high interior wall temperature, thus this method would have lesser efficiency in medium or high-rise residential building cases.

Passive heating methods

Insulating the building envelope is one of the most common ways to improve heating efficiency in a cold climate, and it also contributes to the cooling efficiency in hot climates. For example, a study evaluated wall insulation in the hot summer - cold winter climate city of Shanghai, with results showing that both heating and cooling energy decreased, although heating energy decreased to a greater degree (Pan, Chan, Deng, & Lin, 2012). High performance windows are highly regarded for decreasing the heat escape from the envelope in the winter time. However, research shows that they also contribute to improving the cooling efficiency in a hot climate. Tahmasebi, Banihashemi and Hassanabadi, (2011) have reported that the triple glazed window has better effectiveness than double glazed window regarding energy demand for various window-to-floor ratios within the hot and humid climate of Malaysia. Moreover, a decrease of between 3.4-6.4% in cooling energy by replacing the single glazing with double low-E glazing was recorded in a similar study from Malaysia (Sadrzadehrafiei, Sopian, Mat, & Lim, 2011).

In conclusion, although active heating and cooling are necessary under the hot summer and cold winter climate, there are still passive means that provide thermal comfort during inter-season months and are able to reduce the energy demand of active methods. However, the factors that need to be considered when deciding on a passive retrofit strategy are the climate condition of a given location and the specific building geometry and surrounding environment (Tejero-González et al., 2016).

2.3.3. Housing situation in Hunan

According to the latest report from the China Association of Building Energy Efficiency (CABEE), there was a total of 67.1 billion m^2 of existing building floor area in China in 2018, of which 30.3 billion m^2 (45%) and 23.8 billion m^2 (36%) were in urban and non-urban areas respectively (CABEE, 2020). Hunan province has a population of 14.5 million living in cities, 10.1 million in counties (a lower administrative level of the city) and 10.5 million in rural areas (including towns and villages) (MOHURD, 2019a). While Hunan is situated in a relative densely populated region (the hot summer - cold winter climate region) of China, its per capita housing area is relatively large compared with other provinces in this region, with 49.6 m^2 in the urban area and 63.9 m^2 in the rural area (Hunan Statistical Yearbook, 2020). Thus, there are many existing residential buildings in Hunan, and the building area difference between urban and non-urban areas should not be significant.

In Hunan province, the differences between urban and non-urban residential buildings are more of geometry, size and design than of building materials. The modern urban residential structures (Figure 2-6) are mostly in high-rise apartment buildings (more than 10 storeys) with several flats in one floor and are usually situated within density populated surroundings. In suburban areas (Figure 2-7), most modern residential structures are low-rise and medium-rise flats buildings, which usually only have one flat on each floor and are usually built in rows along the street. For rural areas (Figure 2-8), most residential buildings are low-rise dwellings in which the layout of function rooms may be scattered on different floors, and they usually have more open surroundings. In terms of building materials, their structures are mostly built with concrete and steel, and brick is the primary material for the envelope; and the windows mostly consist of a single layer of glass (Xiong, Liu, & Kim, 2019). According to the China Association of Building Energy Efficiency, (2020), steel and cement are the top two materials associated with carbon emissions and are responsible for 45.5% and 21.3% of the total embodied carbon of national building material production. Fortunately, those existing residential buildings built in the past several decades are structurally sound and are expected to function for many years. Thus, proper retrofitting of those buildings to suit occupants' increasing expectations for the comfort of modern life could be the sustainable means to make the best use of those energy-intensive building materials.

Figure 2-6 : Urban residential buildings in Hunan province.

Figure 2-7: Town (suburban) residential buildings in Hunan province.

Figure 2-8: Rural residential buildings in Hunan province.

2.3.4. Energy consumption of existing housing

As an overview of the building sector in China, the energy consumed during the operational stage was responsible for 21.7% (about 1 billion tonnes coal equivalent) of the 2018 national energy consumption, in which urban and rural housing accounted for 37% and 24%, respectively. Considering different climate regions, the northern heating area (including both cold and severe cold climate regions) took the most prominent energy consumption proportion, but its proportion has been declining in the last two decades because the focus of energy consumption has been changing to the southern hot climates regions, with the hot summer - cold winter climate region having the fastest yearly operational energy growth rate (10.3%) and its energy consumption in 2018 took 29% of total national building related energy consumption (CABEE, 2020). In addition, considering the need for active heating and cooling is increasing in this climate region, its energy demand is expected to have a significant increase in close future (Z. Wang et al., 2015).

In Hunan province and other hot summer – cold winter climate regions, the air conditioning system is the main method that supplies both heating and cooling and it is assisted by electric fans in summer and plug-in heaters in winter, which only radiate heat in a small area (Z. Wang et al., 2015). The carbon emissions from space heating and cooling had increased nearly three times in urban areas, and slightly more than two times in rural area during the 1996 and 2012 (Fan, Yu, & Wei, 2015). The average number of air conditioners per 100 households in China has been increasing rapidly in recent years, Figure 2-9 shows the situation between 2013 and 2018, and the population has increased by 35 million during this period (National Bureau of Statistics, 2020), and in Hunan province, this number has reached 122.6 air conditioners per 100 households in 2018. Chen and Yoshino, (2009) validated the trend of building electricity consumption in the hot summer – cold winter region based on a major city in this region, Shanghai, and a dramatic increase from 55 kWh/capita-year in 1980 to 574 kWh/capita-year in 2005 was highlighted.

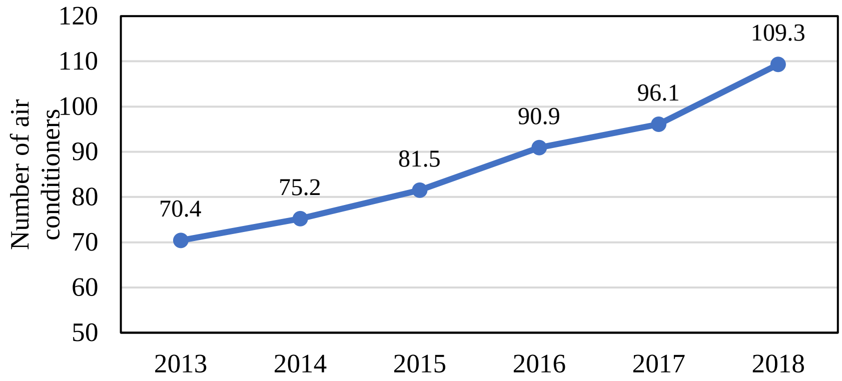


Figure 2-9: Change of the number of air conditioners per 100 households in China in recent years, source from National Bureau of Statistics (2020).

2.3.5. Thermal comfort of existing housing

Due to the heating policy in China, for which central heating systems are not provided in the hot summer - cold winter climate region, the residents in this region for a long time had to adapt themselves to the extreme weather. As living standards improve, air conditioning is becoming the main active method which the occupants utilise to condition the poor indoor thermal environment resulting from the hot summer and cold winter climate, and therefore, the energy consumption for heating and cooling has been increasing (Delmastro, Lavagno, & Mutani, 2015). However, Wang *et al.*, (2015) investigated 513 households' energy consumption and concluded that (i) 84% of the household occupants chose to turn on the air conditioner in winter when they were at home and feeling cold, (ii) 90% of the studies occupants felt cold when indoor temperature drop below 12°C, and (iii) 73% of them selected to turn off the air conditioner for heating during sleep. This suggested that the hours for which the occupants had a relatively comfortable conditioned indoor environment were not long, and the overall comfort level should not be considered satisfying compared with many international standards.

For the actual indoor thermal environment under the studied climate region, on-site indoor temperature data were recorded in an urban and a rural residential building, which were built before 2005 and 2010, respectively, by Xiong, Liu and Kim, (2019). Both types of buildings were measured under a mixed-mode situation in which the buildings were under free-running conditions most of the time, and the air conditioner was turned on when the occupants felt it was required. Figure 2-10 shows a summary of the recorded data, where the indoor mean temperatures were both around 30ºC and 10ºC in summer and winter respectively in both urban and rural housings, and the different between indoor and outdoor environment were not significant. These results are actually close to those found in this research's monitored thermal data, illustrated in Chapter 3, Figure 3-4. Xiong, Liu and Kim, (2019) also investigated occupants' thermal feelings under this climate through 2171 issued questionnaires (with 513 responses), for which the rural residents showed higher tolerance to the indoor thermal condition than the urban residents. However, both of them showed a strong preference for cooler summer and warmer winter indoor environments.

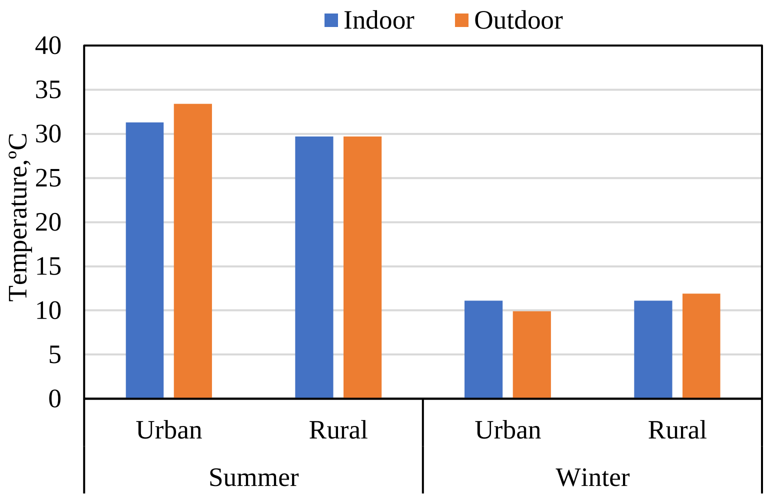


Figure 2-10: Measured indoor and outdoor mean air temperature in existing residential in hot summer - cold winter climate region, source from Xiong et al. (2019).

In general, the indoor thermal comfort under the hot summer - cold winter climate could be considered poor. A large-scale field survey on indoor thermal environments carried out by Li et al., (2018) concluded that the thermal comfort in this climate region was the worst among China's five climate zones. However, there is no doubt that the need for better thermal comfort in this region are increasing as well as the energy consumption for heating and cooling.

2.3.6. Retrofitting standards

Regarding the importance of building regulations and assessment criteria for retrofitting outcomes, it is necessary to know the difference in requirements between the current Chinese regulations for Hunan province and some of the advanced international standards.

Mandatory regulations in Hunan

China's first mandatory building energy saving regulation (code: JGJ 26-86) was issued in 1986, and only focused on residential buildings in northern China, as this part of China is supplied with district heating that consumes a large amount of coal. Since then, the building energy regulations have improved over time. Currently, three national regulations are mandatory for residential buildings under the different climate regions in China. For the studied climate in this research, the regulation on '*Design standard for energy efficiency of a residential building in hot summer, cold winter zone* (JGJ 134-2010)' is applied to most residential building types, including new builds and retrofits and extensions. For Hunan province, specifically, a mandatory local regulation '*Design standard for energy efficiency of a residential building in Hunan* *province* (DBJ 43/001 - 2017)' was published in 2017 and is supposed to be strictly enforced in conjunction with the current national regulation (JGJ 134-2010) for all of the new buildings in this region. Table 2-1 summarises the main requirements of the two above mentioned regulations.

As shown in Table 2-1, the mandatory requirements for the residential buildings under the studied climate region are mainly focused on building designs and envelope thermal performance. The building design requirements are basically the same for the national regulation and Hunan local regulation, while the requirement in envelope thermal performance is relatively higher in Hunan regulation, especially for window performance. For the building energy performance, both the standards aim to achieve a 65% energy saving in yearly active heating and cooling consumption compared with the condition that no measures about improving envelope thermal performance and efficiency of heating and cooling system were applied. However, this energy goal is not included as part of the mandatory policy.

Table 2-1: The main requirements of the mandatory Chinese building regulations for the studied climate type.

Parameters		JGJ 134-2010 (National regulation)	DBJ 43/001 – 2017 (Hunan regulation)
Building shape factor (ratio between envelope area and interior volume)	3 floors or less 4 – 11 floors 12 floors or more	0.55 0.40 0.35	0.55 0.4 0.35
Window to wall ratio (WWR)	North façade East, west façade South facade	0.4 0.35 0.45	-
Envelope heat transfer coefficient (shaper factor ≤ 0.4)	Roof Exterior wall Exterior window	U≤0.8 when D≤2.5 U≤1.0 when D>2.5 U≤1.0 when D≤2.5 U≤1.5 when D>2.5 U≤4.7 when WWR≤0.2 U≤4.0 when WWR 0.2-0.3 U≤3.2 when WWR 0.3-0.4 U≤2.8 when WWR 0.4-0.45	U≤0.6 when D≤2.5 U≤0.8 when D>2.5 U≤0.8 when D≤2.5 U≤1.1 when D>2.5 U≤3.6 when WWR≤0.2 U≤3.2 when WWR 0.2-0.35 U≤2.8 when WWR 0.35-0.45 U≤2.5 when WWR >0.45
Envelope heat transfer coefficient (shaper factor > 0.4)	Roof Exterior wall Exterior window	U≤0.5 when D≤2.5 U≤0.6 when D>2.5 U≤0.8 when D≤2.5 U≤1.0 when D>2.5 U≤4.0 when WWR≤0.2 U≤3.2 when WWR 0.2-0.3 U≤2.8 when WWR 0.3-0.4 U≤2.5 when WWR 0.4-0.45	U≤0.5 when D≤2.5 U≤0.6 when D>2.5 U≤0.9 when D≤2.5 U≤1.0 when D>2.5 U≤3.2 when WWR≤0.2 U≤2.8 when WWR 0.2-0.35 U≤2.5 when WWR 0.35-0.45 U≤2.3 when WWR >0.45

U: heat transfer coefficient, W/m^2K;
D: index of thermal inertia, it is a dimensionless index that characterizes the decay rate of the envelope structure to the periodic temperature wave in its interior, the larger the value, the better the thermal stability of the envelope structure;
WWR: window to wall ratio.

Currently, the mandatory policy in China is more focused on new buildings in urban areas. For example, the mandatory policy of the 'five-year plan' between 2015 and 2020 was to achieve at least 50% green building among the entire new built urban buildings and achieved 20% energy efficiency improvement in the new built compared with the average energy efficiency level in 2015 (MOHURD, 2017). Similarly, the current local policy for 2021 in Hunan province is for the newly built green buildings to account for 70% of the total construction this year (MOHURD, 2021). However, 'Green building' certification in China involves markings from many elements such as safety and geometry design, the factor of energy saving only accounts for about 20% of the certification, and requirement is focused on envelope thermal performance, rather than a clear indicator about energy consumption or saving (MOHURD, 2018).

Voluntary regulations in China

Building energy conservation and green building have been seen as important factors in China's sustainable development by the Chinese ministry of housing development. To this purpose, voluntary building regulations based on the advanced international standards and policies were published for guiding green development in the building sector. Among these, technical guidelines for passive ultra-low energy green building and technical standards for nearly zero energy buildings (GB/T 51350-2019) are the two regulations with the highest standards for energy-saving recommendations. Those two regulations have different criteria for different climate types in China. For the studied hot summer - cold winter climate, Table 2-2 illustrates the main technical measures, including thermal envelope, airtightness level and building system, for those two regulations, and Table 2-3 shows their energy criteria. Moreover, both regulations suggest a comfort indoor air temperature of 20ºC or higher in winter and 26ºC or lower in summer. Those two voluntary regulations have significantly higher requirements for the envelope thermal performance when compared with the mandatory regulations for residential buildings in the same climate region. Moreover, the two voluntary regulations also have requirements for airtightness level, and the usage of heat recovery functioned mechanical ventilation system to improve energy efficiency. As a result, they specify a very low energy demand. When compared with the buildings that achieved the mandatory regulations and reviewed earlier, the passive ultra-low energy building should at least achieve an energy saving of 85% in active heating; the nearly zero energy building should achieve an energy saving between 60% and 75% in overall building energy consumption; and the ultra-low energy building should achieve an overall energy saving of 50% *(MOHURD, 2015, 2019b)*. However, those two voluntary regulations currently do not provide specific guidance and requirements for new builds compared to retrofits.

Table 2-2：Comparison of main technical measures for the hot summer - cold winter climate region between two voluntary regulations in China, source from (MOHURD, 2015, 2019b).

Parameters	Technical guidelines for passive ultra-low energy green building	Technical standard for nearly zero energy buildings
Roof	U: 0.20~0.35	U: 0.15~0.35
Exterior wall	U: 0.20~0.35	U: 0.15~0.40
Ground floor	-	-
Exterior window	U: 1.0~2.0	U: ≤2.0
MVHR system	Sensible heat recovery 75% Enthalpy heat recovery 70%	Sensible heat recovery 75% Enthalpy heat recovery 70%
Airtightness	0.6 ach	1.0 ach

U: U-value, W/m^2k.

Table 2-3: Comparison of energy criteria for the hot summer - cold winter climate region between two voluntary regulations in China source from (MOHURD, 2015, 2019b).

	Technical guidelines for passive ultra-low energy green building	Technical standard for nearly zero energy buildings	
		NZE building	ULE building
Heating energy	5 kWh/m^{2}a	8 kWh/m^{2}a	10 kWh/m^{2}a
Cooling energy	3.5+2.0*WDH_{20} +2.2*DDH_{28} (34.1 kWh/m^{2}a)	3+1.5*WDH_{20} +2.0*DDH_{28} (27 kWh/m^{2}a)	3.5+2.0*WDH_{20} +2.2*DDH_{28} (34.1 kWh/m^{2}a)
Sum of heating, cooling and lighting	60 kWh/m^{2}a	-	-
Sum of heating, cooling, hot water and lighting	-	55 kWh/m^{2}a	65 kWh/m^{2}a

NZE: nearly zero energy; ULE: ultra-low energy; WDH_{20}: wet-bulb degree hours against baseline of 20ºC; DDH_{20}: dry-bulb degree hours against baseline of 28ºC.

Advanced international building regulations

From a global perspective, developed countries in Europe recognised the environmental consequences and undertook the development of sustainable buildings relatively early. Several essential policies intent on reducing building energy consumption have been formulated, among which the Energy Performance of Building Directives (EPBD) by the European Commission in 2010 is a leading policy action (Economidou et al., 2020). The critical measure EPBD set up for building energy conservation was the implementation of nearly zero energy buildings (NZEBs), for which new buildings for public authorities have been required to be NZEBs since December 31, 2018, and all new buildings have had the NZEB requirement since December 31, 2020. Each member state is required to detail the definition of NZEBs and set up a plan for NZEB implementation according to their national or regional condition (*EPDB*, 2010). Therefore, the definition and criteria for NZEBs differ slightly from country to country, but, in general, NZEBs should have a very high level of energy efficiency and very low energy consumption requirement for operation. D'Agostino and Mazzarella, (2019) collected the numeric indicators of energy performance for NZEBs expressed as primary energy among different European countries and grouped by climate types and building type, and Table 2-4 shows the indicators for dwellings.

Table 2-4: NZEBs level of energy performance for residential building under different European climates, source from (D'Agostino & Mazzarella, 2019)

Climate, and represetive cities	Primary energy (kWh/m^2a)	On-site renewable energy (kWh/m^2a)	Net primary energy* (kWh/m^2a)
Mediterranean (Catania, Athens, etc.)	50 - 65	50	0 - 15
Oceanic (Paris, London, etc.)	50 - 60	35	15 - 30
Continental (Budapest, Milan, etc.)	50 - 70	30	20 - 40
Nordic (Stockholm, Helsinki, etc.)	65 - 90	25	40 - 65

- Off-set between the primary energy and on-site generated energy.

Besides NZEBs, there are other advanced building concepts, such as zero carbon buildings and energy plus buildings, and for each of these, the aim is to achieve as little energy consumption in building operation as possible and produce energy carriers from suitable renewable energy sources on-site or nearby to partly or fully offset the small amount of consumed energy or even rest energy that could be returned to the grid. Among all those advanced concepts, achieving a very low building energy consumption is a fundamental element.

2.4. Passivhaus EnerPHit standard

2.4.1. Passivhaus principles

The Passivhaus concept was developed by the Swedish Professor Bo Adamson and the German Professor Wolfgang Feist in the 1980s, based on the idea of creating a type of housing that required even lower energy than the low-energy houses which existed at that time, through making use of the climate conditions and integrating with the existing energy saving technologies (*Passipedia n.d.*). Then, the Passivhaus standard was established from the laws of building physics and combined elements such as architecture and energy efficiency technologies to establish energy efficiency requirements (Müller & Berker, 2013). The criteria of the Passivhaus standard are shown in Table 2-5 and

Table 2-6 below, in which the heating demand limit is 15 kWh/m^2a for all new buildings, and the requirements for retrofits are slightly different according to the climate type. The Passivhaus standard does not require any specific technical solution, but the criteria are supposed to be achieved by fulfilling the five basic principles that are considered the foundation and essence of the Passivhaus concept - thermal insulation, windows, airtightness, ventilation with heat recovery, and thermal bridge free design (*Passipedia*; Müller and Berker, 2013).

Thermal insulation

The Passivhaus standard has a strict requirement on thermal insulation for creating an envelope enclosure which insulates the indoor and outdoor environments, such that accordingly the amount of energy consumption for maintenance the indoor thermal comfort could be minimised (*Passipedia*). For Passivhaus in cool and moderate climates in Europe, the U-value, which represents the heat transfer efficiency, is limited to a value no greater than 0.15 W/m^2K for the entire opaque envelope (*International Passive House Association*). For achieving such a low heat transfer efficiency, extra insulation is usually required (Karimpour, Belusko, Xing, & Bruno, 2014).

Windows

The transparent part of the envelope contributes 20% to 30% of the total heat loss through the whole envelope, although it usually accounts for a much smaller area than the opaque envelope (Lin et al., 2021). The Passivhaus standard requires windows with particularly low U-values of between 0.70 and 0.85 W/m^{2}K to decrease the heat loss from this part of envelope (Yang Wang, Kuckelkorn, Zhao, Spliethoff, & Lang, 2017). Windows with this level of thermal performance are mostly combined with triple low emissivity glazing and filled with krypton or argon gas in between the panes of glass that have been carefully sealed with the window frame (Feist, Schnieders, Dorer, & Haas, 2005). Currently, the high performance windows among tripled glazed windows could achieve a U-value around 0.6 W/m^{2}K. The amount of heat gain received through this type of high performance window is actually higher than the heat loss from them during winter time when facing south (Yang Wang et al., 2017).

Airtightness

The Passivhaus standard requires a super airtight envelope for which no more than 0.6 air changes per hour (ach) are allowed through the envelope infiltration for avoiding thermal energy loss through unwanted ventilation (PHI, 2016b). Airtightness performance is an uncertainty when selecting envelope component combinations because it is highly correlated with the volume of warm/cool air transfer through the envelope and thus affects the entire envelope's thermal performance (Badescu & Sicre, 2003a). The lower the envelope infiltration rate is, the better the airtightness performance is. The actual level of airtightness is often measured by a blower door test conducted on-site after the construction is completed (Hsu, Zheng, Cooper, Gillott, & Wood, 2021). Thus, the airtightness level remains unknown until the Passivhaus standard is tested.

Ventilation with heat recovery

The Passivhaus standard aimed to create a super insulated and airtight envelope which would result in a minimum amount of heat loss, so the windows are normally supposed to be kept closed to retain the indoor heat source. However, this causes the need for fresh air to be provided by a mechanical ventilation system but combined with heat recovery function, with the fresh incoming air gaining heat from the outgoing indoor air (Yang Wang et al., 2017). Thus, the ventilation with heat recovery could provide indoor thermal comfort while reducing the need for active heating. A heat recovery rate of at least of 75% is required by the Passivhaus standard (PHI, 2016b). Mechanical ventilation is practically meaningful when the outdoor temperature is too far from a comfortable level, but during mild months the indoor temperature can be similar to outdoor temperature, and so natural ventilation is still an efficient and recommended way to improve air quality and comfort (Yang Wang et al., 2014).

Thermal bridge free design

A thermal bridge conducts indoor heat towards the outside, reducing the efficiency of heating the indoor space (*Passipedia*). Thermal bridges usually occur when two envelope components of different thermal conductivities meet, such as joints, corners and punctures happen in the envelope due to necessary building work such as piping. Particular attention must be paid to the areas where thermal bridges are likely to happen in order to form an unbroken insulation layer to the envelope (Badescu & Sicre, 2003b). Moreover, the Passivhaus standard suggests that the interior envelope surface temperature should be always kept above 13ºC for avoiding a cold bridge (Feist et al., 2005).

2.4.2. Passivhaus criteria

The Passivhaus concept is undoubtedly one of the most important guides for achieving a low energy demand in building operation. Energy efficiency and indoor thermal comfort are the main indices considered by the Passivhaus standard. The Passivhaus standard considers new builds and retrofits and holds each to different criteria. For the new builds, strict criteria are applied for all climates worldwide, while for retrofit projects, a classification of seven climates zones is considered, and different requirements are given based on climate zones due to the likelihood of more difficulties and limitations in the existing structure, meaning that retrofits may not be able to achieve as strong energy efficiency as new builds. Table 2-5 and Table 2-6 show the relative criteria for new builds and retrofits. Renewable energy generation is also within the boundary of the Passivhaus standard, which is classified by plus level and premium level, while the Passivhaus without energy generation is classified as classic level. The plus and premium levels require a renewable energy generation of 60 kWh/m^2a and 120 kWh/m^2a respectively.

Table 2-5: Passivhaus criteria for new buildings, source from (PHI, 2016b).

			Criteria	Alternative criteria
Heating	Heating demand (kWh/m^2a)	≤	15	-
	Heating load (W/m^2)	≤	-	10
Cooling	Cooling+dehumidification demand (kWh/m^2a)	≤	15 + dehumidification contribution	-
	Cooling load (W/m^2)	≤	-	10
Airtightness (1/h)		≤	0.6	-

Table 2-6: EnerPHit standard for retrofitted buildings, source from (PHI, 2016b).

Climates	Arctic	Cold	Cool-temperate	Warm-temperate	Warm	Hot	Very hot
Heating demand (kWh/m^2a)	35	30	25	20	15	-	-
Cooling+dehumidification demand (kWh/m^2a)	Equal to criteria for new builds						

2.4.3. Passivhaus performance

The first Passivhaus built in Darmstadt, Germany in 1991, is considered as the beginning of the Passivhaus movement in Germany and Austria, which spread to other parts of Europe and then all over the world. With the rapid development of Passivhaus projects in the last two or three decades, there has been a large amount of Passivhaus structures built and much research conducted on it, in areas such as its energy performance, thermal comfort, life cycle studies and optimisation analysis.

The performance of Passivhaus in terms of energy and comfort has been widely proven, especially in Europe and cold climate regions (Rohdin, Molin, & Moshfegh, 2014). In Europe, over 100 Passivhaus buildings were investigated as part of the CEPHEUS project, and they achieved a space heating demand which was 15-20% of that for standard new buildings, and the indoor temperature did not exceed the comfortable range between 20-25ºC for 95% of the period of the measured summer months (Schnieders & Hermelink, 2006a). A 55-83% reduction in energy consumption was claimed in the Passivhaus standard retrofitting of historic buildings (Moran, Blight, Natarajan, & Shea, 2014). A study examined nine Passivhaus structures built in Sweden and found an average annual heating demand of 21 kWh/m^2a, which is in line with the Swedish Passivhaus criteria, but also that the demand could rise to 35 kWh/m^2a when the heating set point is increased from 20 to 24°C. Moreover, this research highlighted that overheating in summer could happen if no exterior shading was installed (Rohdin et al., 2014). For a Passivhaus in London, the monitored results showed an annual heating consumption of 12.1 kWh/m2a and primary energy demand of 125 kWh/m^2a, while the occupants reported a comfortable winter indoor environment, with an average temperature of 22.4°C in the living room. However, summertime overheating was observed, and so the authors suggested window operating is an efficient way to avoid overheating (Ridley et al., 2013).

Schnieders, Feist, & Rongen (2015) examined a particular form of Passivhaus dwelling in six different climate zones around the world. The resulting Passivhaus annual energy demand for space conditioning was 75-95% lower than for a traditional building Wang et al. (2017) reviewed the energy performance of frequently used Passivhaus technologies and their interaction with indoor environment quality in Passivhaus buildings under different weather conditions. Requirements and strategies regarding the Passivhaus standard in residential building in different countries have been reviewed in different countries (Guillén-Lambea, Rodríguez-Soria, & Marín, 2016). More recently, Passivhaus buildings are being built in warmer climate regions, with some of these buildings reporting summer overheating or cooling demand being higher than the Passivhaus requirement (Badescu et al., 2010; Fokaides et al., 2016).

However, for achieving the strict energy criteria of Passivhaus and the EnerPHit standard, significant adaptations to the entire envelope fabric, airtightness and mechanical systems of the building are involved (Huang, Binti Wan Mohd Nazi, Yu, & Wang, 2020). Therefore, Passivhaus buildings require extra materials to successfully attain the criteria (Karimpour et al., 2014). The manufacture of those extra materials can consume a large amount of energy and cause significant carbon emissions, which are expected to be factored into the construction process of Passivhaus buildings (Karimpour et al., 2014). For example, a life cycle study of a Belgian Passivhaus suggested that the embodied energy, which is the energy used for a material's production, could represent 40-56% of the building's total energy consumption in a 100 years lifespan (Stephan, Crawford, & Myttenaere, 2013). A similar study of a Chinese Passivhaus hotel building close to Shanghai (within the hot summer – cold winter climate zone) found that the embodied energy accounted for 24.3% of the total energy demand over a 70-year lifespan and that this demand was about 42% higher than the embodied energy if the building had been constructed according to the local building regulation requirements (Su, Tian, Shao, & Zhao, 2020). Therefore, the embodied energy represented a significant share over the building's lifetime, but it is currently not factored into the investigation of Passivhaus criteria (Sierra-Pérez, Rodríguez-Soria, Boschmonart-Rives, & Gabarrell, 2018; Thormark, 2002).

To improve the Passivhaus life cycle performance, studies about optimisation or of minimising the initial impact of implementing Passivhaus are considered significant. For instance, there is a rising need to identify the suitable insulation properties of each envelope element and the combination of the envelope elements to balance the retrofitting inputs and the energy-saving effort after retrofit (Annibaldi, Cucchiella, De Berardinis, Rotilio, & Stornelli, 2019). Sierra-Pérez et al., (2018) analysed different retrofitting solutions for a university building in Spain, and concluded that the amount of insulation material played a strong role in terms of a renovation's life cycle performance, and the selection of insulation material with lower carbon and energy inputs (such as cork) would reduce the impact of renovation.

In conclusion, the energy efficiency of Passivhaus has been widely proven, with significant improvement in thermal comfort compared with conventional buildings. However, examining Passivhaus through a life cycle method is considered as a more comprehensive way to determine the performance of Passivhaus.

2.4.4. Selecting Passivhaus EnerPHit standard for the Hunan housing

For the existing housing stock in Hunan Province, as reviewed earlier, most of the existing structures are built with carbon-intensive building materials such as steel and cement, and even those built in recent years failed to meet the Chinese national mandatory building regulations (Lin et al., 2020). One way to balance the impact of these carbon emissions on the environment is to extend the life of these dwellings as much as possible. For the suburban Hunan dwellings, fortunately, many of them were built in recent decades and are expected to function for many more years to come. At the same time, the structures are solid but simple, basically composed of a concrete frame and brick shell, so there are not many building materials that need to be dismantled for retrofitting.

However, energy-saving renovation of buildings has been under development for many years, and it was realised that profitable technological solutions are not sufficient to reach the ambitious energy saving goals (Müller & Berker, 2013). Passivhaus can lead to 80-90% energy saving compared with traditional buildings, and so Passivhaus is considered to be one of the most effective ways to reduce building energy consumption (H. Liu & Ding, 2018), and Passivhaus EnerPHit standard retrofitting has a high potential to bridge the gap between the high energy consumption in existing building stock and the building energy saving targets (Müller & Berker, 2013). On the other hand, the Chinese government is constantly updating the requirements for building energy saving, and continuously retrofitting the existing buildings towards the changing standards should not be considered as a sustainable solution, as many problems such as repeated construction and resettlement of residents would result. Passivhaus standard retrofitting should be a long-term solution that a significant decrease in building energy consumption could be expected. Moreover, buildings retrofitted to such a high level should have a longer service life with less maintenance work.

2.4.5. Experience from the Passivhaus buildings in China

In China, the Passivhaus standard is a relatively new concept, as it was first introduced in 2008. The first certified Passivhaus was the Hamburg House at the 2010 World Expo in Shanghai. Since then, China has cooperated with Germany and implemented 44 pilot Passivhaus projects with a total floor area of 420,000 m^2 in 10 provinces of China's climate zones, most of which are in the northern provinces of Shandong and Hebei (M. Lu & Zhao, 2018; Ren, Tu, & Zhou, 2017). To promote the growth of Passivhaus implementations in China, two building regulations associated with the Passivhaus standard (reviewed in section 2.3.6) were released by the Chinese government, and based on its green building development plan, demonstration Passivhaus projects will be carried out in different climate regions in China. Furthermore, based on those experiences, design guidelines will be developed for each region (Lin et al., 2021). However, there are still much fewer Passivhaus cases in the south, especially in non-urban areas, and the EnerPHit standard retrofitting is even less familiar in southern China.

For the energy performance of the Passivhaus in China, all of the certificated 51 Passivhaus projects in China have achieved 15 kWh/m^2a or less for space heating, based on certification information (Passive House Database). Moreover, according to

Lin's review of about six built Passivhaus in China, the heat recovery efficiency of the ventilation system was recorded between 75% and 80%, and the most commonly used indoor environmental conditioning system was the ground source heat pump (GSHP) system. For energy efficiency, an energy saving between 85% and 95% was recorded in those Passivhaus, compared with existing housing (Lin et al., 2021).

As for more detailed studies, Yang's investigation about four Passivhaus projects built in northern China illustrated that the commonly used insulation materials are XPS, Rockwool and Graphite polystyrene board. For all of the four Passivhaus buildings, a double layer insulation system was adopted in which the exterior layer of insulation was thicker than the interior layer of insulation, and the average insulation thickness for the exterior wall and roof was 250mm and 300mm respectively. For the energy demand, the simulated results show that the Passivhaus only requires 46% of the total heating and cooling energy if the buildings have been built in accordance with the local energy saving standard- which already required a 65% energy saving compared with the conventional building (Yang, Wu, & Liu, 2017).

As part of a study that assessed the difference in energy performance for buildings built to Passivhaus standard compared to the local energy saving standard in Beijing, which has an outdoor temperature range from -10ºC to 35ºC, a residential building that includes 24 flats was modelled by the software EnergyPlus. Due to the mechanical ventilation system with heat recovery (MVHR) not being required by the local standard, the energy load was compared between the two cases when the MVHR system was not in operation. Based on the simulated results, the main difference was found in heating load, as the load was 7.3W/m^2 in the Passivhaus case but was 14.5 W/m^2 in the local standard case, while the cooling loads were similar - which were

10.8 W/m^2 and 11.8 W/m^2 respectively. Furthermore, an MVHR system with a heat recovery efficiency of 75% was simulated on the Passivhaus case, and the fresh air supply volume was found to be a factor that influences the energy demand. The total energy demand changed from 33.35 kWh/m^2a to 22.66 kWh/m^2a when the fresh air supply volume decreased from 90 m^3/h to 30 m^3/h per person, and this was an energy conservation between 5.5%-11.2%, based on the level if the MVHR system was not applied (Zhang, Hao, & Liu, 2015).

Song, Wu and Yu, (2016) carried out a study based on a high-rise Passivhaus project located in Tianjin, which is situated in the cold climate region in China, although it should be noted that the mean temperature in July could reach 29 ºC. This research highlighted architectural design characteristics from the practical experience of this project, including compacted building shape design for decreasing the envelope area, window design that reduces the partition of the window frame to the glass, and the appropriate selection of the zones that should be insulated. The simulated result based on the actual feature of this Passivhaus showed a heating demand of 14.1kWh/m^2a, which was within the requirement, but the cooling demand (25.0 kWh/m^2a) was beyond the requirement, and there was an overheating rate of 28% against the temperature benchmark of 25 ºC. Moreover, this research identified that wall insulation was the most significant element that influences the heating demand, followed by the efficiency of the MVHR system and window performance based on parametric analyses. However, the energy saving efficiency declined when the wall insulation thickness exceeded 260mm. Passive cooling methods and other cooling energy saving practices were not considered in this research.

In accordance with Passive House certification information (*Passive House Database*), detailed information of some of the Passivhaus were collected in Table 2-7 for understanding the achieved technical measures and the achieved energy performance under different climate conditions in China. The envelope insulation of the presented Passivhaus buildings all achieved low U-values, despite the variance in insulation thickness due to the climate type and building geometry. Those projects in the hot summer regions each applied a Mechanical Ventilation and Heat Recovery (MVHR) system with an extra humidity recovery function because of the relatively humid climate. Moreover, active cooling seems necessary for many parts of China based on the reviewed cases - whether the dominant energy consumption is for heating or cooling depends on the climate zone.

Among the Passivhaus cases reviewed in Table 2-7, case no.5 is located in Hunan province, the location of this research. The hygro-thermal performance of this Passivhaus was recorded for 24 hours in August 2019 during a short visit. The measured data, presented in Figure 2-11, suggest a comfortable indoor environment with a stable temperature of about 24°C and a relative humidity level of around 40% to 50%, while the outdoor temperature changed between 28.1°C and 36.2°C and the outdoor humidity was between 46% and 76%. Moreover, Ruge, (2014) analysed the energy performance of the first residential Passivhaus in southern China shown as no.6 in Table 2-7, and an efficient energy saving was indicated by the author, which was 95% energy savings compared to local conventional dwellings. At present, most Passivhaus buildings in China are trial projects led by the government and real estate companies to promote the concept and development of the Passivhaus standard.

Table 2-7: Some certified Chinese Passivhaus projects

	1	2	3	4	5	6	7
Passivhaus buildings							
Location	Harbin	Hebei	Hebei	Shanghai	Hunan	Zhejiang	Fujian
Climate	Severe cold	Cold	Cold	HSCW	HSCW	HSCW	HS/WW
Building	Office	House	Flat	Office	Flat	Hotel	Terrace
TFA	3943m^2	496m^2	3633m^2	116m^2	6468m^2	1940m^2	1102m^2
Year	2017	2017	2018	2018	2017	2013	2017
Leakiness	0.6 ach	0.5 ach	0.15 ach	0.6 ach	0.33 ach	0.42 ach	0.38ach
Wall insulation	320mm EPS	250mm EPS	300mm Mineral wool	380mm Rockwool	160mm EPS	200mm EPS	200mm EPS
U_W-value (W/m²K)	0.11	0.12	0.13	0.16	0.21	0.16	0.17
Floors insulation	300mm EPS	350/200mm XPS	240mm EPS	200mm XPS	160mm EPS	-	60mm XPS
U_F-value W/m²K	0.09	0.10	0.17	0.17	0.20	0.81	0.55
Roof insulation	400mm EPS	250mm XPS	300mm EPS	350mm Rockwool	200mm XPS	230mm PU spray foam	240mm XPS
U_R-value (W/m²K)	0.09	0.14	0.11	0.11	0.15	0.14	0.15
U_W-value (W/m²K)	0.79	0.80	0.85	0.80	0.79	0.79	0.74
U_D-value (W/m²K)	0.75	1.40	0.85	0.78	0.77	-	1.00
MV system; heat, humid recovery	80% -	Lowcarn 90.4% -	Zehnder 88%,65%	Zehnder 85%,62%	Wonderful 88%, 77%	Climavenet a, 71%, 68%	Zehnder 75%, 51%
Heating/ cooling	AC with MVHR	ASHP	AC with MVHR	AC	ASHP	ASHP	AC
H demand (kWh/m^2)	13	15	14	13	1.3*	15	1.0
H load (W/m^2)	17	11	10	14	4.3	15	7
C demand (kWh/m^2)	5	16	17	27	25.8	33	32
C load (W/m^2)	9	5	7	11	18.4	10	10
PE (kWh/m^2)	101	-	119	95	116	109	95

**Offset with the power generated by PV panels. Acronyms: Hot summer - cold winter (HWCW); Hot Summer/Warm Winter (HSWM); U-Value for wall (UW); U-Value for roof (UF); U-Value for floor (UF); Air conditioning (AC); Air source heat pump (ASHP); Heating (H); Cooling (H); Primary* *energy use (PE).*

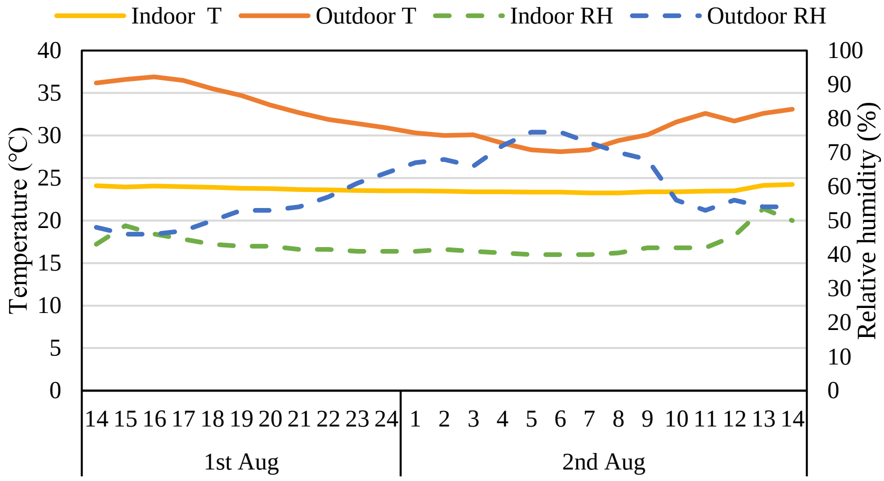


Figure 2-11: Field measured air temperatures (T) and relative humidities (RH) in a Passivhaus project in Hunan for 24 hours.

From the findings of previous studies, the carbon emissions during the building use phase usually contribute the largest proportion over all life stages (Cuéllar-Franca & Azapagic, 2012; Ibn-mohammed, Greenough, Taylor, Ozawa-meida, & Acquaye, 2013), but for buildings with high energy efficiency standards, the carbon emissions from the building materials (embodied phase)are usually responsible for a much larger or even the largest share among the whole lifecycle (Gustavsson & Joelsson, 2010; Verbeeck & Hens, 2010). Moreover, for the same lifecycle period, the percentage of energy consumption and carbon emissions of a building usually has a similar share in each life stage (Rodrigues & Freire, 2014).

A life cycle study based on a Passivhaus project in southern China (no.6 in Table 2-7) was carried out by Su et al., (2020), and assessed in comparison to the case that the same building was built to the local building design code. This study considered the building life cycle in two parts, for which the embodied stage includes material production, transportation, onsite construction and the disposal/recycling at the end of building life, while the operational stage encompasses the impact from 70 years of building operation. For the Passivhaus case, the total embodied carbon was 0.98 tCO_2-e/m^2, for which the use of concrete was responsible for the largest share of 31.8%, with the share for insulation material and cement use being similar, being 12.8% and 12.6% respectively, while the onsite construction only was responsible for 1% of the total embodied carbon. For the conventional case, however, the total embodied carbon was 14% lower than the Passivhaus case, being 0.84 tCO_2e/m^2. The operational carbon emissions were calculated from the operational lifespan and the annual energy consumption simulated by the software EnergyPlus, which were 38.6 kWh/m^2a for the Passivhaus and 52.7 kWh/m^2a for the conventional case. Thus, the percentage of the embodied carbon generated over the 70 years lifespan in the Passivhaus case was 29.5% of total carbon emissions of 2.58 tCO_2e/m^2, and this total emission was 22.7% lower than what the conventional case would generate. This research showed that a Passivhaus project releases more carbon in the embodied stage than conventional buildings, but that the whole life carbon emissions are less due to the savings that could be achieved in the operational stage. However, this research calculated the operational carbon by a simple method, for which the impacts from climate changes which may occur during building's lifespan were not considered.

Cost is another important factor that affects the promotion of Passivhaus in China. A case study for a high-rise residential building in the cold climate zone in China which was retrofitted towards the Passivhaus standard collected the costs of the retrofitting materials, and analysed the cost benefit through a simple payback time which did not consider the monetary inflation (Huang et al., 2020). The results suggested that the cost payback period for the retrofitting plan was 18.4 years. However, the cost inventory of the retrofitting materials collected in this study was partly based on similar products in the local market, while the cost of the same product that achieves the Passivhaus standard required performance is expected to be higher.

As for research based on actual Passivhaus operation, a complex analysis of the multiple operation strategies of a three-floor office Passivhaus built in Henan province was carried out by Chen et al (2021). The general energy performance of this Passivhaus was calculated by PHPP (Passivhaus certification software) based on the actual features of the building, and the results showed an annual heating demand of 14 kWh/m^2a and cooling demand of 16 kWh/m^2a. The achievable performance of this building, with the applied mechanical systems and passive methods in terms of energy and comfort during the actual operation, was assessed for different times of the year. A period of a year was divided into four ‘seasons’ by the author according to on-site recorded weather characteristics, which were the hot summer season, hot and moist summer season, cold winter season and mild spring and autumn season. Multiple operation schemes involving different combinations from building systems were designed and tested in actual building operation for each season, which included a GSHP system powered floor radiant system, a fresh air system and a fan coil system, and passive methods of external sunshades and natural ventilation. The energy consumption and thermal comfort were analysed separately for the building operation of each of the designed schemes. However, to clearly identify the optimal operation method for the building under each of the different weather conditions (the four seasons), the author proposed a performance indicator that combined the energy consumption (kWh) and thermal comfort (predicted mean vote) for evaluating the schemes. The final results marked by the author were as follows. The fresh air system combined with GSHP or fan coils was the best option for the hot summer season. The fresh air unit combined with fan coils as well as GSHP was the superior option for the hot and moist summer season, although the dehumidification process took up to 4 hours. For the mild season, natural ventilation supplied through the fresh air system alone was the optimal solution. For the cold season, the best solution was to use fan coils cooperated with the radiant flooring, and frequent start and stops of the system should be avoided (Y. Chen et al., 2021). This type of research which helps to understand the real performance of the Passivhaus should be considered as high value, but the numbers of this type of research are very limited due to the Passivhaus projects in China being relatively few.

In conclusion, although the projects in China suggest that substantial operational energy use in buildings could be reduced by achieving the Passivhaus standard, these projects are mostly newly built high-rise buildings in northern urban areas. Those experiences in northern climates should facilitate the Passivhaus development in hot climates in China to a certain degree, as they all have requirements in both heating and cooling, but to different degrees due to the different dominant weather conditions. Examples of where buildings have been retrofitted towards the corresponding Passivhaus standard are very limited, even though upgrading the energy performance of the numerous existing residential buildings is imperative in order to achieve energy-saving goals. Moreover, it is currently the case that the related policy and regulations about Passivhaus and low energy building in China mainly focus on the design and a fixed energy performance, but the importance of whole life cycle impacts and evaluation system ought to be given more consideration by academics and representatives of government (Zhijian Liu, Zhou, Tian, He, & Jin, 2019).

2.5. Conclusion

Energy retrofitting of existing dwellings is significant for sustainable development, so there has been an improvement in retrofitting technologies and energy saving targets across the world. The beginning of this chapter reviewed the retrofitting measures being used and analysed in China, and it was found that a systematic retrofitting framework has already been identified in China, though the research involving comprehensively evaluating the retrofit effects such as life cycle assessment is relatively weak. Combined with the analyses of the housing situation and building regulations under the hot summer - cold winter climate region in the second part of this chapter, it was clear that the Chinese government had in the past neglected the thermal comfort needs of the housing in the southern part of China, resulting in an urgent need to mitigate the rapidly increasing housing energy consumption due to increased comfort needs for current and future development. However, this climate region's current compulsory building regulations are not ambitious enough to achieve an efficient green intervention.

Passivhaus EnerPHit standard retrofitting is regarded as an efficient solution since its effects have been widely proven. However, it can be seen from the review of Passivhaus development in China so far, in the third part of this chapter, that current research about Passivhaus energy performance is limited to the small number of pilot projects in China which are mostly located in the north, and there is a clear research gap in Passivhaus standard retrofitting studies. Therefore, this study aimed to investigate the effects of Passivhaus standard retrofitting under the Chinese hot summer - cold winter climate through a case study of a typical suburban residential building located in the southern China province of Hunan, which experiences a hot summer - cold winter climate.

Chapter 3. Case study

3.1. Case building introduction

This research's case study building is a typical semi-detached four-storey residential/commercial building constructed in 2006 in Huilong town (Figure 3-1). Huilong town is in the southwest of Hunan province and is situated in the hot summer – cold winter climate region of China. Figure 3-1 and Figure 3-2 demonstrate the location of Hunan province and the case building respectively. This particular building was selected for the following reasons. Firstly, in the last few decades, the residential buildings in town and villages within the hot summer - cold winter climate region in China have been largely replaced with mid-rise reinforced concrete structured new-builds. These have no thermal insulation or any energy efficiency measures, and so these buildings require large amounts of energy to support a comfortable indoor environment. However, they are structurally solid with an expectation of a long lifespan. The selected case building is representative of those residences. Secondly, access to enough information of a case study is significant to research. The proprietor of this residential building permitted the thermal data recording in their property, provided construction specifications and other needed building information for carrying out this study.

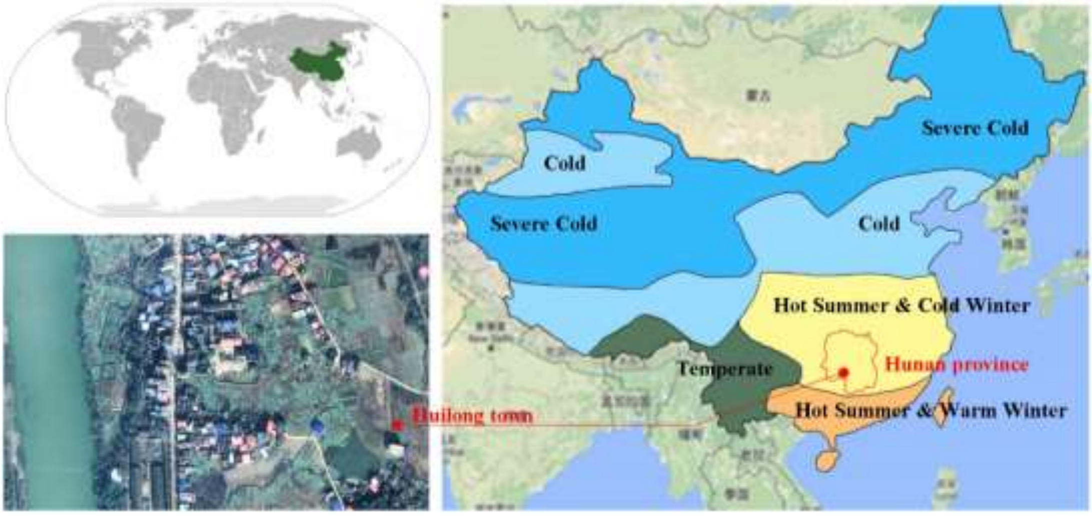


Figure 3-1: View of the Huilong case building and its location in Hunan province

Figure 3-2: View of case building (semi-detached dwelling on the right).

The ground floor of the case building is used as a commercial space, which is common for town dwellings in Hunan province as businesses usually gather together in towns to service the surrounding villages. The top three floors are three individual flats that share the same layout shown in Figure 3-3. The patio in this building functions as a light well to bring natural light to the living room, and one of the bedrooms and its space are connected with the staircase space (as their divider is a low wall on each floor rather than a full-length wall). The decision was made to exclude the ground floor from retrofitting as it is a commercial space, as was the patio and staircase space because their floor areas accounted for around 23 m^2 on each floor but are much less used by the occupants. Therefore, only the flats area was considered for retrofitting, and each flat has a floor area of about 99 m^2. Table 3-1 provides detail of the construction materials of each envelope components and their U-values. It was unexpected that the interior wall had a slightly lower U-value than that of the exterior wall, as they were made by basically the same materials. The reason for this was found to be that the thermal conductivity of the most outside layer (5mm putty paint) of the interior wall (0.4 W/mk) was better than the most outside layer (10mm porcelain) of the exterior wall, which was 1.3 W/mk.

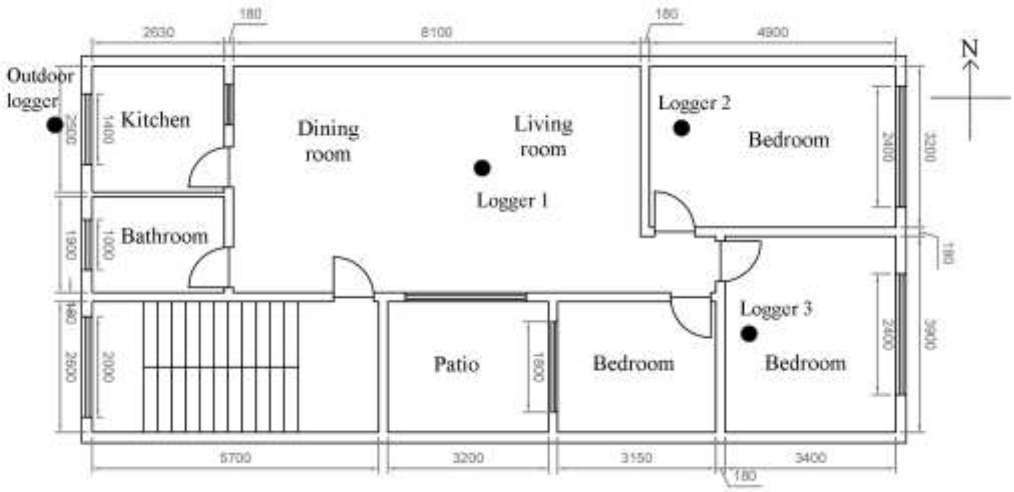


Figure 3-3: Floor plan and data logger locations (●)

Table 3-1: Constructional and material information of the case building

Components	Construction detail	U-Value (W/m^2K)
Exterior wall	5mm putty paint, 10mm cement mortar, 180mm clay brick, 10mm cement mortar, 10mm outside porcelain tiles	2.32
Interior wall	5mm putty paint, 10mm cement mortar, 180mm clay brick, 10mm cement mortar, 5mm putty paint	2.30
Roof	50mm cement, 100m reinforced concrete raft, 400mmair gap, 10mm wood board, 5mm putty paint	1.90
Ground floor	20mm Rammed earth, 10mm gravel, vapor membrane, 100m reinforced concrete, 50mm Terrazzo 10mm porcelain tiles, 10mm cement, 50mm cement mortar,	1.30
Internal floors	100m reinforced concrete raft, 5mm putty paint	2.44
Windows	4mm single glass, Aluminium window frame	5.85

3.2. Monitoring concept

Environmental condition measurements were taken in two periods in one of the flats within the case building (second floor), which was occupied by a full-time working couple. Indoor environment, temperature and relative humidity in the living room and second bedroom were recorded by Rotronic HL-1D devices; a Rotronic CL11 was used to record the CO_2 levels, temperature and relative humidity in the master bedroom. For the outdoor environment, temperature and relative humidity adjacent to the property were measured by an EasyLog EL-GFX-2. Figure 3-3 indicates the location of each logger. All indoor loggers were placed on top of a shelf or wardrobe where they were not exposed to direct sunlight and kept away from heat sources. The outdoor logger was placed in a naturally-ventilated box underneath a shelter and so was not exposed to direct solar gain. The two recording periods were 23rd January to 21st February 2018 (one month) and 1st July 2018 to 30st June 2019 (twelve months).

Electricity was the primary energy source used in the case building, so electricity usage was considered for assessing the actual energy consumption. The consumed electricity amount was recorded by the monthly electricity bills between July 2018 and June 2019 (twelve months).

3.3. Monitoring equipment and settings

Three different items of monitoring equipment, Rotronic HL-1D, Rotronic CL11 and an EasyLog EL-GFX-2, were used for recording conditions in the case building. Those devices were all new and used for the first time when measuring the case building, so their factory calibrations were accepted. Table 3-2 presents each type of logger's specifications and the location in which each was placed. All the indoor loggers were recording at a 15 minutes interval, while the outdoor logger was recording at 20 minutes to save the battery life. However, the outdoor logger ran out of battery from 22nd to 27th March 2019, so the missing data were requested from the China meteorological information centre; the data source was from the weather station closest to the case building, Dongan weather station.

Table 3-2: Data loggers and sensors specifications

	Rotronic HL-1D	Rotronic CL11	EasyLog EL-GFX-2
Data loggers			
Measurement range	Temp: -20ºC to 70ºC RH: 0 to100%	Temp: -20ºC to 60ºC RH: 0 to100% CO_2: 0 to 5000ppm	Temp: -30ºC to 80ºC RH: 0 to100%
Accuracy	Temp: ±0.3 ºC RH: ±3%	Temp: ±0.3 ºC RH: ±2.5% CO_2: ±30ppm	Temp: ±0.35 RH: ±2.05
Recording location	Living room, 2nd bedroom	Master bedroom	Outdoor
Recording interval	15 minutes	15 minutes	20 minutes

3.4. Monitored results

3.4.1. Temperature and relative humidity

The monitored results presented in this section came from the second measurement period, as it covered a full year, and so the outdoor weather context and indoor environmental condition could be presented comprehensively. The usage of the data recorded in the first measurement period (one-month time) will be explained in later sections. The whole building was naturally ventilated and not heated/cooled actively during the measurement periods, except for the recorded master bedroom, which used an air conditioning during the sleeping time on hot summer nights. In addition, data measurements in the master bedroom were disrupted a few times due to unpredictable power outages. Thus, the indoor temperature and relative humidity were determined with the average value between the living room and second bedroom to demonstrate a free-running indoor thermal environment.

An overview of indoor and outdoor comparisons in recorded temperature and relative humidity is shown in Figure 3-4. A large outdoor temperature range was recorded over the 12 months, and the monthly mean temperature varies from 6.2°C to 31.1°C, with a monthly average high temperature of 37.7°C in July and an average low temperature of 4.5°C in January. The outdoor recorded highest and lowest temperatures were more extreme, as the values were 41.1°C and -0.3°C, respectively. Compared with the outdoor temperature, the indoor situation was more stable but not enough to be comfortable. The indoor monthly mean temperature was always around 1°C higher than the outdoor condition and changed between 6.6°C and 32.3°C, with the monthly average high temperature of 33.1°C in July and average low temperature of 6.3°C in January. Regarding the relative humidity, both indoors and outdoors had comparatively high values, and the winter months were more humid than the summer months. The monthly mean relative humidity level was between 69% and 89% outdoors and between 61% and 88% indoors.

Overall, the recorded data suggested that the case building's location has a typical hot summer - cold winter climate with a fairly high relative humidity level all year round. Because the case building was constructed with basic materials, and no insulation was applied, the measured results show that the indoor thermal environment was very close to the outdoor situation. Consequently, thermal comfort level was considered unsatisfactory, especially in the summer and winter months.

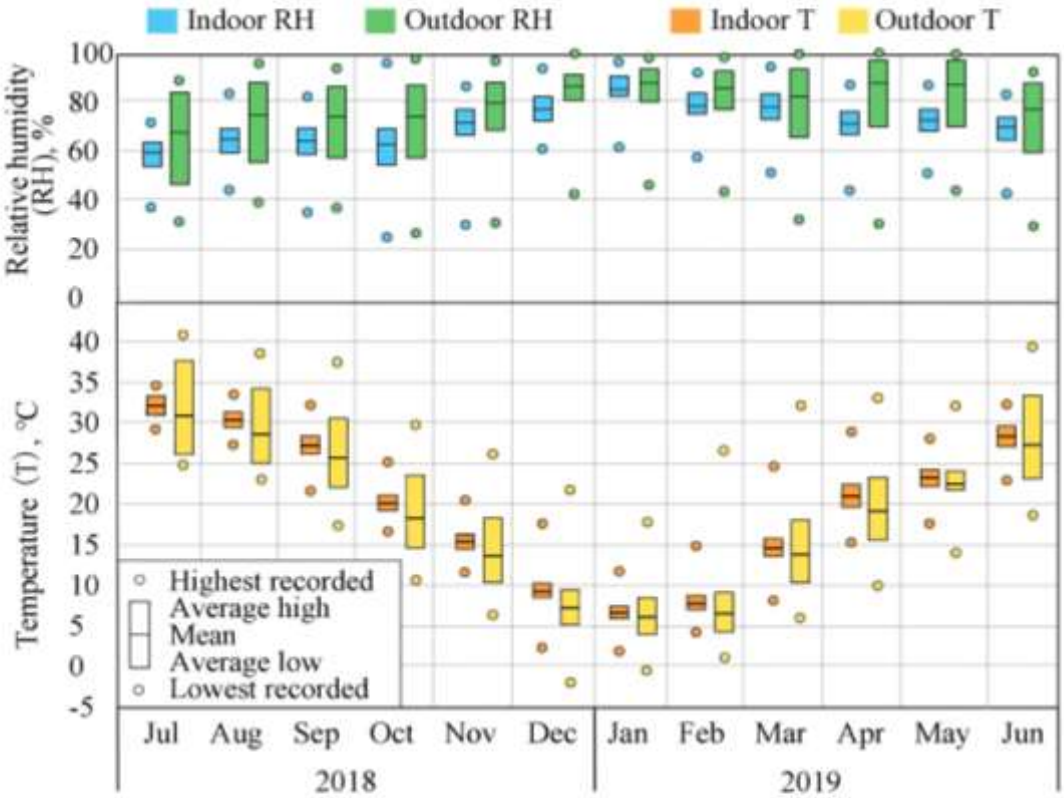


Figure 3-4: The recorded indoor and outdoor measured air temperature and relative humidity data for the one-year period (July 2018 to June 2019).

Figure 3-5 and Figure 3-6 present a closer look at the recorded indoor and outdoor environmental condition in the hottest month (July) and coldest month (January). The recorded highest and lowest temperature and relative humidity in those two months are marked in the figures. In July, both the indoor and outdoor temperature had a noticeable daily cycle change, the outdoor temperature had a wide daily change range between 25°C to 41°C, while the change range of indoor temperature was smaller, between 29°C and 35°C. The outdoor daily peak temperature usually appeared around 3.00 pm, and after 2 to 3 hours, the indoor heat mass built up and reached the peak; the daily low temperature in external conditions was monitored mostly around 6.00 am, and after about one hour, the heat inside the building dissipated to the minimum.

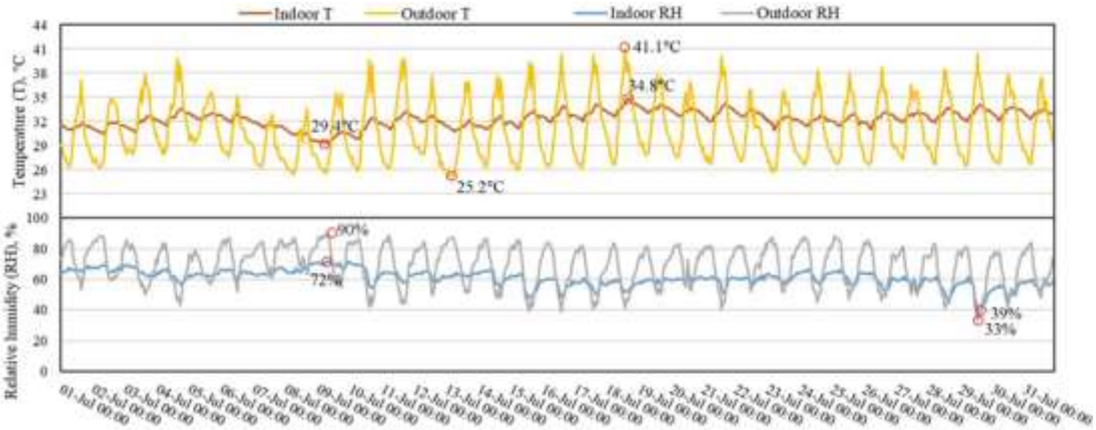


Figure 3-5: Comparison between indoor and outdoor environment in July

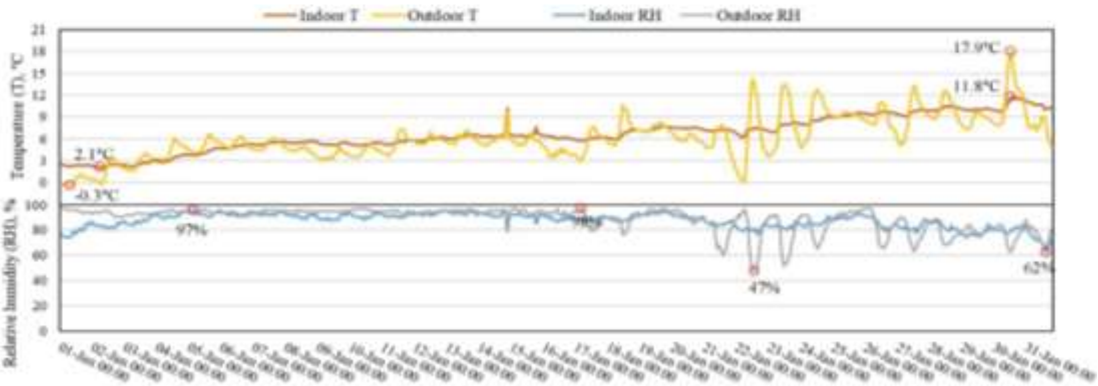


Figure 3-6: Comparison between indoor and outdoor environment in January

In January, the outdoor temperature also shows a recognisable daily change cycle. The daily peak temperature was monitored to appear around 3.00 pm to 5.00 pm, and the daily low value usually appeared at around 6.00 am to 8.00 am. The trend of indoor temperature followed the outdoor change but had no distinct daily cycle. The daily mean temperature in this month was between 2.3°C to 10.7°C inside the building and 0.3°C to 11.5°C in the outdoor environment. The recorded result showed that the indoor temperature was even lower than the outdoor temperature on some days or hours. This could be out of expectation for people not familiar with this climate, but it is a fact under free running condition that is caused by both the weather and the poor building thermal performance, where the solar heat that the building received and was able to retain in order to warm up indoor space was less than the exposure to the sun that the outdoor environment could receive under a sunny winter day. For the relative humidity, there was a significant difference between July and January, and the indoor daily mean values were 61% and 88% in July and January respectively. Moreover, the outdoor value was recorded to change around 40% and 90% in July, while the range in January was about 80% and 100%, except for the several days which had a very high temperature and, therefore, the relative humidity was heavily affected.

In summary, the recorded data in those two months suggested that the case building's indoor thermal conditions were largely dependent on the outdoor environment. This result reflects many existing suburban dwellings in the hot summer – cold winter climate in China, as the case building shares typical characteristics with other properties.

3.4.2. Indoor CO_2 levels

The indoor CO_2 levels were monitored in the master bedroom to evaluate the indoor air quality, and the CO_2 logger was powered by a mains electricity socket directly rather than a battery. However, due to several unexpected power outages during the measurement period, the data logger for recording the CO_2 level was interrupted several times. As a result, the CO_2 level was only continuously recorded for three months of July, December and January. *CIBSE Guide A* (2016), recommends an indoor CO_2 level of about 800 to 1000ppm for an adequate indoor air quality when the outdoor CO_2 level is around 350 to 400 ppm (Butcher & Bonnie, 2016). The user guide for the measurement device for this research, Rotronic CL11, recommended a range of 800 to 1200ppm for an indoor environment, with an optimum value of 800ppm and maximum value of 1400ppm. The recorded data in the master bedroom is shown in Figure 3-7 and Figure 3-8. Both Figures illustrate an apparent daily change. The lowest daily CO_2

level in each case was around 500ppm over the recorded three months, while there was a big difference in daily peak values between the summer months (around 1500ppm) and winter months (varying between 1500 and 3000ppm). The explanation could be that the occupants slightly opened the window or used air conditioning during summer nights, and in winter, the window was closed or slightly opened during the sleeping time for relatively warmer winter nights. Through statistical measurements, it was found that the value was below 1000ppm 78%, 68% and 65% of the time in July, December and January respectively, and the value was beyond for 23%, 32% and 35% of the time in those three months respectively. In conclusion, the recorded room had a relatively fresh indoor air during daytime when the room was adequately naturally ventilated. In contrast, during night time, the air quality was not satisfactory, especially in winter when the window was closed most of the time to keep the warm temperature indoor.

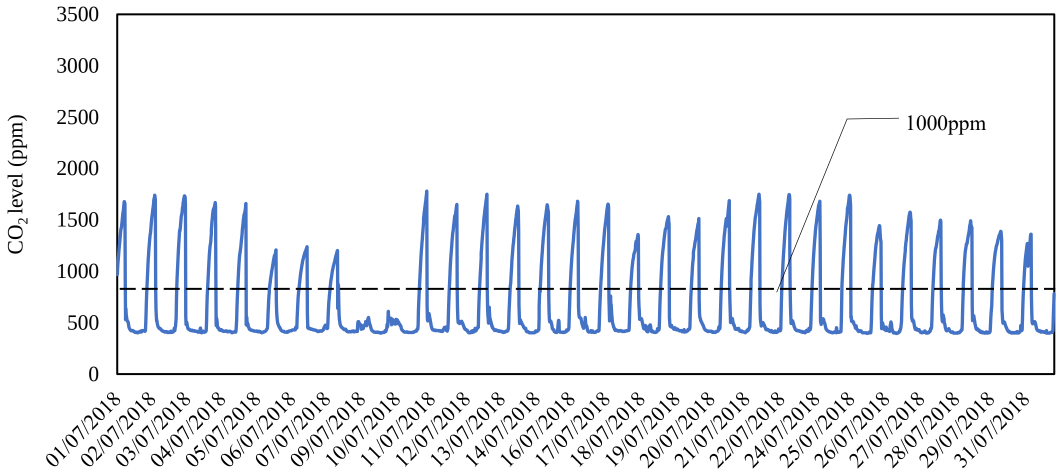


Figure 3-7: Hourly CO_2 level recorded in July 2018.

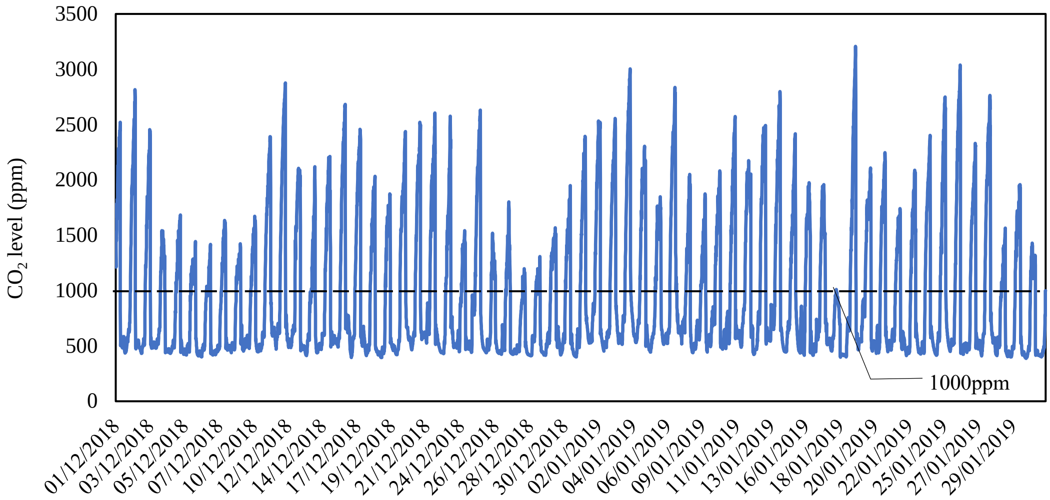


Figure 3-8: Hourly CO_2 level recorded between December 2018 and January 2019.

3.4.3. Electricity consumption

The energy consumption of the same second floor flat in the case study building was also assessed during the same period when the monitored environmental conditions were being monitored. The primary energy source of the case building was electricity, and the breakdown of electricity consumption is shown in Figure 3-9, which includes most of the household energy usage, including lighting, appliance socket, auxiliary load, air conditioning, individual heaters, and electric boiler (only for winter use).

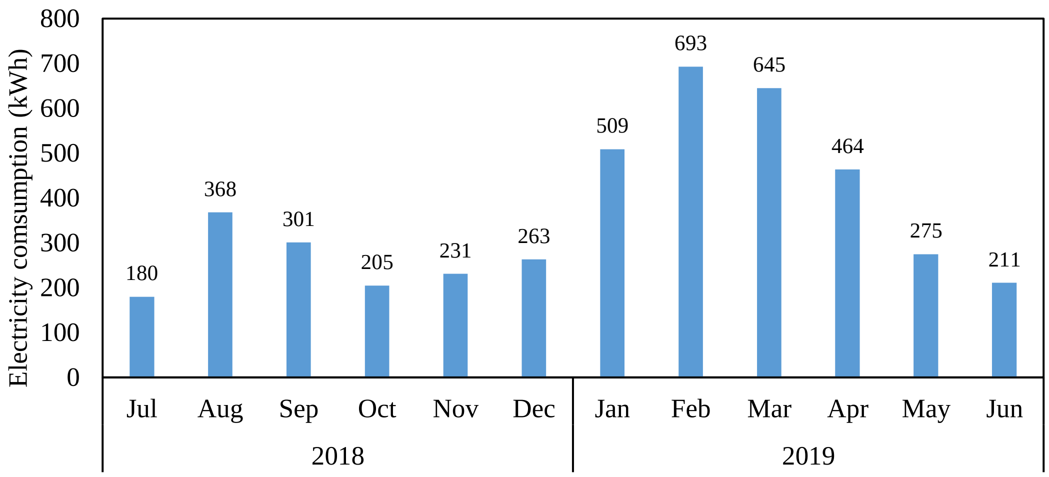


Figure 3-9: Electricity consumption from July 2018 to June 2019.

Hot water in non-winter months was supplied by a solar water heater, an electric boiler was used in winter as the hot water generation from the solar panels is not efficient when the sunlight is weak during winter. Cooking energy was not included because it is powered by liquid gas, for which the occupants did not keep the consumption bills. The total electricity consumed during the recorded 12 months period was 4345 kWh, and the monthly average consumption was 362 kWh. However, the consumption was quite different in different months. In spring and autumn months, like May, September and October, heating and cooling were not needed and the domestic hot water (DHW) was mostly heated by the solar panels, so the electricity consumption in those months should represent the unregulated and lighting energy consumption of the monitored flat, which was around 200 to 300 kWh. Although the occupants used air conditioning in the master bedroom when nighttime temperatures were very hot in summer, the summer's monthly peak consumption was only 368 kWh. In winter, however, the monthly peak consumption was recorded as 693 kWh in February, and the monthly consumption for each month from January to April were all significantly higher than other months. The reason for high electricity consumption in winter was the use of the domestic electric boiler for hot water and electric heaters. The most common electric heaters used in this region are resistive heaters that generate heat when an electric current passes through a conductor (usually quartz tube) with resistance (Zhidong Liu, 2021). Local electric heaters are used in such a way that people approach the heater and even use thin cover to keep the supplied heat very close with them instead of heating the entire room space, which would be very energy consuming and actually beyond the power capacity of the heaters. As reviewed previously, the monthly mean indoor temperature was only 6.6°C and 7.9°C in January and February respectively, and so the indoor temperatures were not really improved because more energy was consumed. Overall, the energy consumption of this flat was much higher in winter than in summer. Combined with the monitored environmental conditions reviewed earlier, the thermal comfort in the case building was considered unsatisfactory, especially in the summer and winter months, no matter that higher energy consumption was recorded.

3.5. Existing thermal comfort

In this section, the existing indoor thermal comfort of the case building will be evaluated by use of an adaptive model suggested in a Chinese evaluation standard for the indoor thermal environment in civic buildings (*GB/T 50785-2012*, 2012). This standard adopted the same method to generate the adaptive thermal comfort model as with the ASHRAE 55 standard. However, it placed a greater emphasis on Chinese climate types and has separate calculations for the acceptable comfort range for free running buildings in the studied hot summer - cold winter climate, based on extensive field investigation. Therefore, this standard was selected to evaluate the case building's thermal comfort rather than the widely used ASHRAE 55 standard.

By the Chinese standard, the establishment of the comfort model is based on how residents feel about outdoor weather conditions, which could be measured by the outdoor running mean temperature (t_{rm}) where outdoor temperatures, 7 days prior to the test date, are considered for the t_{rm} calculation (see Equation 3-1). The accepted indoor comfort range is calculated by the equations listed in Table 3-3. Comparing the acceptable indoor comfort range under the Chinese standard and ASHRAE 55 standard, the Chinese standard in general allowed a cooler indoor temperature in winter and a warmer indoor temperature in summer as long as the summer is not very extreme (when t_{rm} is around 30ºC or even hotter), and in this case, the ASHRAE standard allows a warmer indoor temperature (ASHRAE, 2017; GB/T 50785-2012, 2012).

$$t_{rm} = (1 - \alpha)(t_{od-1} + \alpha t_{od-2} + \alpha^2 t_{od-3} + \alpha^3 t_{od-4} + \alpha^4 t_{od-5} + \alpha^5 t_{od-6} + \alpha^6 t_{od-7})$$

Equation 3-1

where: $\alpha = 0.8$ (recommended value by the standard);

t_{od-n} = outdoor daily mean temperature of the n days prior to the test day (°C).

Table 3-3: Thermal comfort evaluation for free-running buildings in hot summer – cold winter climate

Class	Acceptable range	Limitation
Class I (90% satisfied)	$t_{op\ I,b} \leq t_{op} \leq t_{op\ I,a}$ $t_{op\ I,a} = 0.77t_{rm} + 9.34$ $t_{op\ I,b} = 0.87t_{rm} - 0.31$	$18°C \leq t_{op} \leq 28°C$
Class II (75% satisfied)	$t_{op\ II,b} \leq t_{op} \leq t_{op\ II,a}$ $t_{op\ II,a} = 0.73t_{rm} + 12.72$ $t_{op\ II,b} = 0.91t_{rm} – 3.69$	$18°C \leq t_{op\ II,a} \leq 30°C$ $16°C \leq t_{op\ II,b} \leq 28°C$ $16°C \leq t_{op} \leq 30°C$

The monitored outdoor temperature data were brought into those equations to generate the corresponding comfort range for this climate, which is shown in Figure 3-10, and the recorded indoor daily mean temperature during the period between 1st July 2018 and 30th June 2019 is displayed on the same figure to evaluate the thermal comfort of the case building. The results of the first few days of this period could also be displayed in Figure 3-10, since their outdoor running mean temperatures were calculated from the recorded weather data of the several days before 1st July 2018, but those data was not included in other parts of this thesis in order to keep the integrity of a calendar year. The operative temperature was replaced by the recorded indoor daily mean temperature in this evaluation because the radiant temperature, which is required for the operative temperature calculation, was not measured on-site. Actually, under the condition if no radiant heating and cooling system was used inside the building, the operative temperature was very close to the indoor air temperature (GB/T 50785-2012, 2012), and this was confirmed by the DesignBuilder simulated results of the case building. In addition, the indoor daily mean temperature was calculated from the average between the living room and one of the bedrooms rather than the two recorded bedrooms. This was because the master bedroom had air conditioning operated in summer so it was not under a completely free condition.

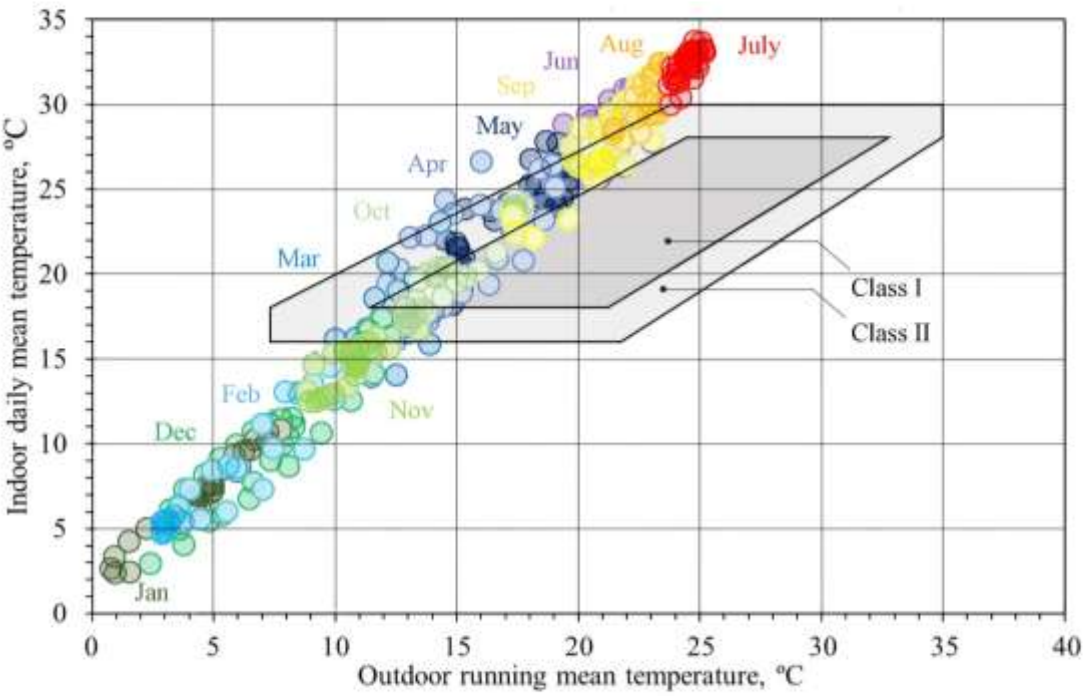


Figure 3-10: Comparing the monitored indoor temperature with the adaptive thermal model

In Figure 3-10, the recorded indoor daily mean temperature is shown in different colours for each of the months, so the thermal comfort at different times of the recorded year could be easily observed. October was the most comfortable month, as the whole month's daily mean temperature was within the comfort range, and 22 days in this month had class I comfort. April and May were also comfortable, with only 2 or 3 days out of the comfort range, though less than one-third of the month was in the class I comfort range. On the contrary, both January and February were both entirely outside of the comfort zone, but January was most uncomfortable because of its lower indoor daily mean temperature. December was also quite cold, and only three days in this month were within the class II range. In July and August, only two and seven days were in the class II range respectively, and the rest of the days were too hot.

Overall, for the recorded one-year time, about 40% of the time (145 days) was in the class II comfort range, and only 13% of the year (49 days) was in the class I comfort range. Moreover, the winter thermal comfort condition was worse than the summer comfort condition, according to Figure 3-10, because the temperatures of the period between December and February were further away from the comfortable ranges than the temperature of the summer months. An adaptive method that the local people use to cope with the cold feeling inside their home is to increase clothing insulation (such as putting on more layers of clothes or changing to a thicker coat) than they may need in the outdoor environment because the occupancy activity level indoors would usually be lower than outdoors. Therefore they would feel colder indoors than outdoors. In conclusion, these results suggest that under the hot summer - cold winter climate, indoor thermal conditions when buildings are in free-running condition hardly meet the expectations for the indoor comfort of modern life. Active heating and cooling for dwellings in this climate range are necessary, but the majority of the existing dwelling’s building performance would lead to very high energy consumption. To achieve both high energy efficiency and thermal comfort in those dwellings, Passivhaus standard retrofitting was regarded as a prospective solution.

3.6. Case building modelling

Having analysed thermal comfort based on the field monitored data, this section moves to the next stage of the study, modelling the selected case building. Firstly, the modelling and simulation software will be introduced, followed by the weather data file for simulations. Then, the modelling details, together with essential inputs for building performance simulations, will be discussed.

3.6.1. *Modelling software–DesignBuilder*

As increasing attention has been paid to energy conservation in buildings by various bodies, such as industry and academia, a good range of building performance simulation software packages has been developed (Attia, Gratia, De Herde, & Hensen, 2012). Among them, DesignBuilder is an excellent example because it operates with the EnergyPlus engine, and its function has been validated by several internationally trustworthy building standards, such as EN ISO 13790 and the ASHRAE standard (*DesignBuilder v6*, 2018). It also has a user-friendly graphical interface which allows the design elements to be changed quickly and the corresponding calculated building performance results to be viewed easily. However, some research states that there are performance gaps between the simulated building performance and the actual performance, which could be caused by absolute variability of occupant behaviour or unpredicted conditions (Lomas & Porritt, 2017). These gaps can sometimes be validated by real measurements, but no actual measurements were available for the retrofitted case building in this study, as the retrofitting measures were virtually applied to the case building to examine the improvement of the building performance. Thus, consideration about performance gap of the retrofitted case building that may be caused by unpredicted variables, was excluded from the DesignBuilder simulation results. DesignBuilder Version 6.1.3 was used in this study, and the University of Liverpool provided the license.

3.6.2. *Weather data file*

To perform complex and accurate simulation of building performance using DesignBuilder it is necessary to use a detailed hourly weather file of the location where the examined building is based. The required weather information, including temperatures (dry bulb and wet bulb), relative humidity, solar radiation and wind speed and direction etc., were formatted into an EnergyPlus Weather (EPW) file. In this study, an EPW file used for the simulation was generated by the climate database software Meteonorm using data from the closest weather station, which is located in Wugang (*Meteonorm (en)*, 2021). This weather file used a synthetic year based on averages among weather data recorded in many years, giving a much longer-term view of the climate, potentially moderating the impact of any unusually cold or hot periods.

3.6.3. Model creation

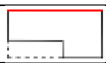
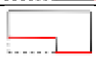
After the suitable weather file was selected, a model was created based on actual features of the case building in DesignBuilder. The considered inputs for the model's creation included geometrical detail, construction materials, and occupancy schedules. Because the case building was running freely during field measurement periods, the HVAC system was set as "off" in the DesignBuilder model, and the model was "ventilated naturally" to match the case building thermal condition. Therefore, the monitored data could be utilised for model calibration.

Table 3-4 shows the case building's basic geometrical information, and Figure 3-3 in section 3.1 suggests the layout of each functional space within the flat's area. The size of each external wall, openings on the wall (windows and doors) and corresponding window-to-wall ratio (WWR) of the space planned for retrofit (flats space) are shown in Table 3-5. The finished 3-dimensional model of the case building can be seen in Figure 3-11, with the semi-detached dwelling adjacent to the case building modelled as a component block for relevant shading or reflection. Because only the flats' area (the three flats on the top three floors with a total floor area of 297 m^2) were planned to be retrofitted, the other spaces in this building were set as semi-exterior unconditioned space, while the wall or floor adjacent to the semi-exterior space were considered as exterior envelope during retrofitting and set as semi-exposed envelope in DesignBuilder simulations.

Table 3-4: Geometry detail of the case building modelling

Number of stories	4
Number of flats	3
Orientation	West to east
Total land area	125.5 m^2 (16.3m × 7.7m)
Total flats area	297 m^2 (99 m^2 for each flat, excluded staircase and patio)
Floor to floor height	2.8 m
Number of occupants	6 (2 in each flat)

Table 3-5: Architectural Geometry detail for each facade of the treated space

	location	Wall area (m^2)	Windows size	Door size	WWR(%)
North		146.7	-	-	-
East		69.3	6 × 4.32m^2 (2.4m × 1.8m)	-	37.4
South		83.7 + 63	3 × 4.32m^2 (2.4m × 1.8m)	3 × 1.8m^2	11.8
West		43.2 + 26.1	3× 2.7 m^2 (1.5m × 1.8m) + 3 × 1.8m^2 (1m × 1.8m)	-	19.5

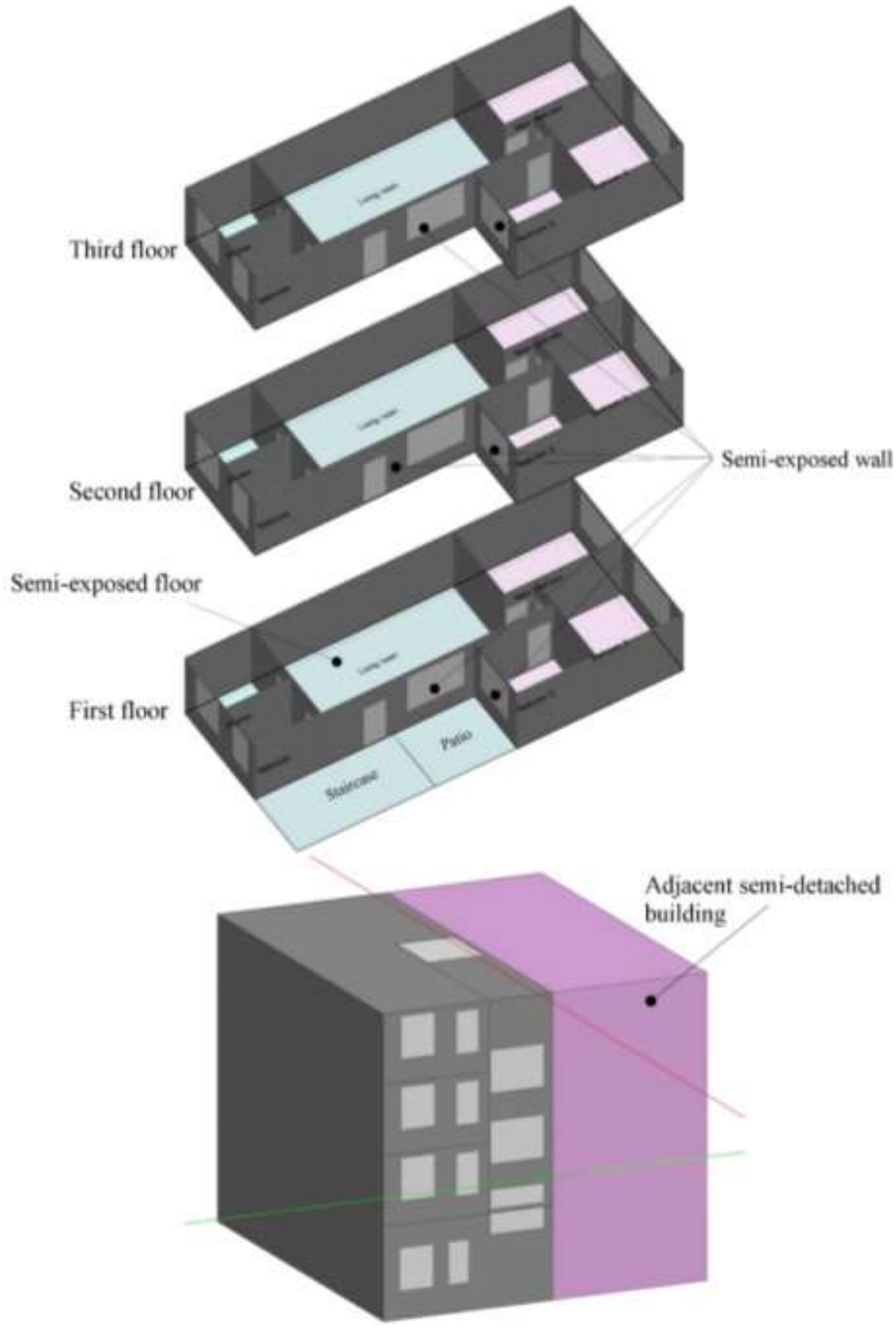


Figure 3-11: The 3-dimensional model of the case building in DesignBuilder.

For construction materials inputs, the detailed building fabrics listed in Table 3-1 in section 3.1 were assigned to each envelope components after the 3-dimensional model was created. The U-values of each of the envelope components, shown in Table 3-1, were calculated by DesignBuilder based on the fabric inputs. Because the case building was constructed from very basic materials like concrete and clay bricks, and no insulation material was used, the envelope has a poor thermal performance, and the U-values of exterior wall, roof, floor and exterior windows were 2.32 W/m^2K, 1.9 W/m^2K, 2.44 W/m^2K and 5.85 W/m^2K respectively. The airtightness of the case building was unknown because it was not possible to acquire an actual measurement due to the limitation of measurement equipment. Therefore, instead, a study by Chen (S. Chen, Levine, Li, Yowargana, & Xie, 2012) that used blower doors was referenced. Chen's work tested several flats' airtightness performance in a building in China that had the same type of construction as the case building, and the measured values were between 1.6 ach to 6.4 ach. The airtightness levels in this range were tested during the calibration stage to determine the closest airtightness level with the case building, and then it was adopted for the following retrofitting.

Internal heat sources like human metabolism, lighting, and household equipment significantly affect the indoor environment results in DesignBuilder. The software calculates person-generated heat based on different metabolic rates, and the metabolic rate inputs illustrated in Table 3-6 follow the guidance from the ASHRAE standard about typical occupant activities in other functional rooms. The inputs for targeted illuminance levels in each room, as shown in Table 3-7, followed CIBSE Guide A. The existing case building was using a low standard lighting pattern with a power density of 5 $W/m^{2,}$ and it was replaced with a LED lightning pattern with a better power density of 2.5 W/m^2 in the later retrofitting stage. Table 3-7 also shows the total lighting energy density in each room for both the existing and retrofit situation. Moreover, the power density inputs of equipment in each room are explained in Table 3-8.

Table 3-6: Occupants metabolic rate inputs for different rooms.

Zones	Metabolic rate
Bedrooms	90W/person
Living room	110 W/person
Bathroom	120 W/person
Kitchen	160W/person

Table 3-7: Lighting inputs for different rooms.

Zones	Target illuminance	Energy density (low standard)	Energy density (LED)
Bedrooms	100 lux	5 W/m^2	2.5 W/m^2
Living room	150 lux	7.5 W/m^2	3.75 W/m^2
Bathroom	150 lux	7.5 W/m^2	3.75 W/m^2
Kitchen	300 lux	15 W/m^2	7.5 W/m^2

Table 3-8: Equipment power density in each room

Zones	Power density
Bedrooms	3.58 W/m^2
Living room	3.9 W/m^2
Bathroom	1.67 W/m^2
Kitchen	30.28 W/m^2

The schedule of occupants activity and building operation is another factor that influences the indoor environment significantly. Several studies have investigated how occupants' behaviour effects the thermal and energy performance of the building, and many of them have concluded that occupants' behaviours vary greatly even in similar conditions and, therefore, predicting and quantifying occupant behaviour to a fixed schedule could be extremely challenging (Porritt *et al.*, 2012; Baborska-Narożny, 2017; Delzendeh *et al.*, 2017). As a result, it was decided to adopt a typical schedule standard that could largely fit most dwellings. The EnergyPlus schedule was adopted for DesignBuilder simulation, which was modified from the UK NCM (National

Calculation Method) (*NCM*) and ASHRAE activity and schedule databases (*DesignBuilder v6*, 2018).

3.7. DesignBuilder model calibration

In order to check the accuracy of the retrofitting performance in the following research, calibration of the baseline model of the case building in DesignBuilder was important. Since the case building was under a free-running situation during the field measurement periods, comparing the field recorded indoor temperature and the DesignBuilder simulated indoor temperature was regarded as a suitable way to validate the baseline model. Because the recorded thermal data between 23rd January and 21st February 2018 (one month) were available first, it was used to calibrate the model through an hourly indoor temperature comparison. Later, when the measurement data between 1st July and 31st December 2018 (six months) became available, it was used to calibrate the model through monthly indoor temperature comparisons. During the validating process, it was found that the adopted Meteonorm weather file in the DesignBuilder simulation was different with the field recorded outdoor weather situation, especially in the summer time. Thus, the field recorded outdoor weather data in July to December 2018 were edited in the original weather file to eliminate the effect upon indoor temperature caused by the different outdoor thermal conditions, so the comparison between the field recorded and simulated indoor temperature shares the same outdoor hygro-thermal condition.

3.7.1. Calibration with hourly comparison

Figure 3-12 displays the average indoor temperature comparisons of each hour from DesignBuilder simulated values and the field measured value between 23rd January and 21st February 2018. Since it was not possible to measure the actual airtightness level of the case building, airtightness levels between 1 ach and 5 ach were tested in DesignBuilder simulations. The results indicated the indoor temperature value was closest to the actual measured value when the airtightness is 3 ach, when the temperature difference was less than 1ºC. It should be possible to objectively show how credible the DesignBuilder model is from the difference between average values per hour of specific periods. However, a comparison of long-term measured values and simulated values could help to prove the credibility of the calibrated model.

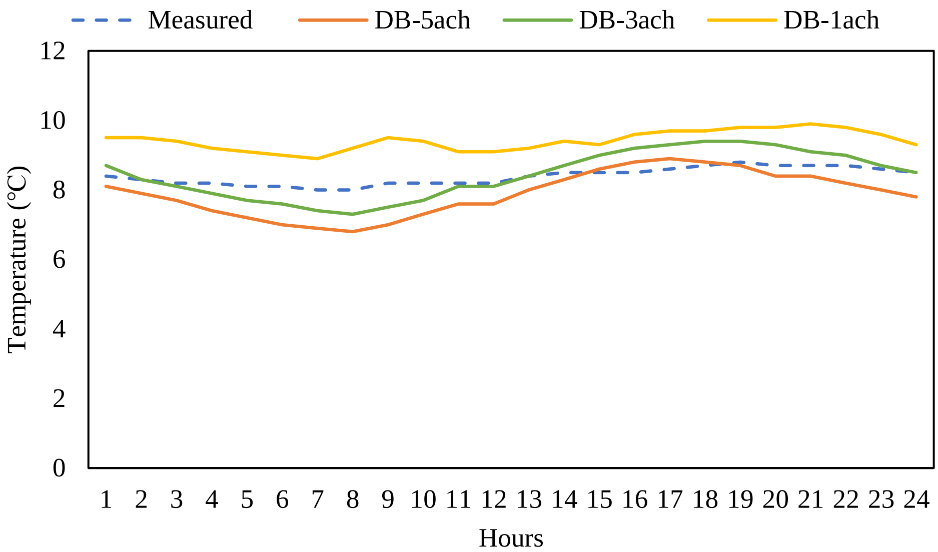


Figure 3-12: Hourly average indoor temperature comparison between the field measured value and DesignBuilder simulated value.

3.7.2. Calibration with monthly comparison

Figure 3-13 draws a 6-months period comparison of monthly average indoor temperatures for the case building between the measured values (July – Dec 2018) and DesignBuilder model simulated values during the same months. The DesignBuilder model was simulated with an airtightness of 3 ach in this comparison since it was previously found to be the most realistic value of the case building. The result shows that a maximum temperature gap of 3ºC occurred in July, with the possible reason later found that the measured outside temperature was also around 3ºC higher to the weather file used in DesignBuilder in the same month. In the winter months, the two outside temperatures were closer, and the two inside temperature values were tending towards the same values.

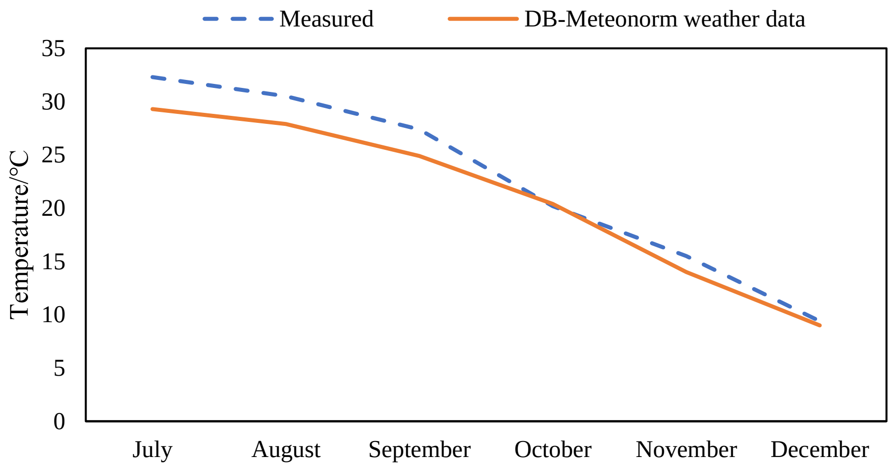


Figure 3-13: Monthly indoor temperature comparison between the field measured value and DesignBuilder simulated value.

3.7.3. Calibration with an edited weather file

To eliminate the effect of the difference between the Meteonorm weather file, and the actual weather conditions, the recorded outdoor weather data were imported into the Meteonorm weather file for model calibration. A free tool, *Elements* (*Elements*, 2021), developed by Big Ladder Software, was utilised for editing the weather file. The recorded outdoor dry bulb temperature and relative humidity hourly data between July and June 2019 were edited in the originally-used weather file; therefore the DesignBuilder model could be checked yearly and under the actual weather condition that the indoor thermal data was recorded. Based on those two weather parameters, *Elements* automatically calculated the wet bulb temperature and dew point temperature, and adjusted the solar radiation relationship. Then, the modified EPW weather file was used in DesignBuilder to perform simulations for model calibration. The calibration results shown in Figure 3-14 suggested a strong correspondence between measured and simulated indoor temperatures, as the largest temperature gap was 0.8 ºC and the smallest gap was only 0.2ºC, which happened in January and April respectively. In addition, calculating CVRMSM (Coefficient of Variation of the Root Mean Square Error) is a recognized approach to calibrate the acceptable difference between the measured values and simulated values according to the ASHRAE guideline. Its criteria consider the model is calibrated when the CVRMSE is less than 15% for monthly comparisons (ASHRAE, 2014). For the 12 months data shown in Figure 3-14, the CVRMSE was calculated 2.5% and was much smaller than the ASHRAE criteria. Thus, the calibration processes were employed principally to validate the baseline model's reliability and give confidence in the simulation of Passivhaus retrofitting. Meteonorm weather data were used in the following retrofitting simulations because it gathered the weather characteristics for many years rather than a specific year.

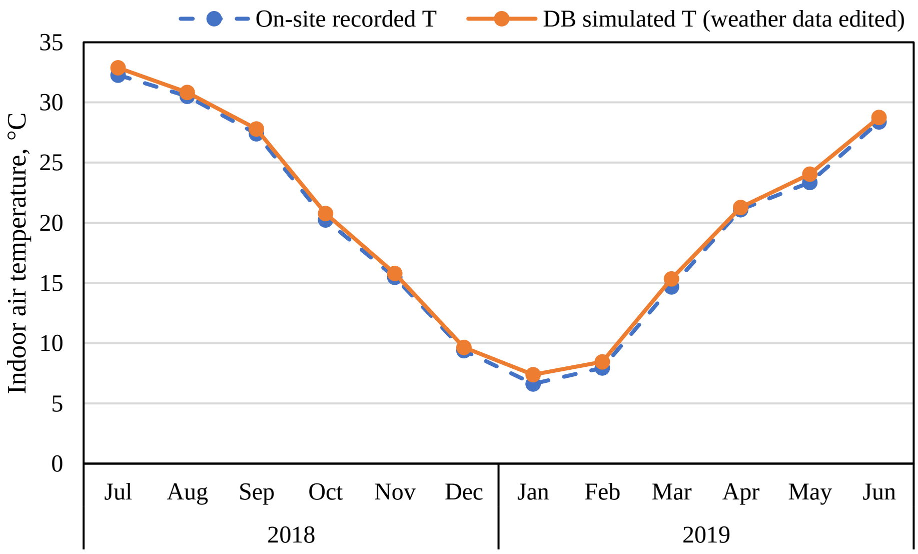


Figure 3-14: Calibration with the monitored weather data employed in the weather file for simulation.

3.8. The baseline model energy performance

In this section, the calibrated baseline model was used to predict the energy performance of the pre-retrofit case building in order to compare with the virtually retrofitted case in later research. In the DesignBuilder simulation for baseline energy performance, a radiator heating system and an air conditioning system were simulated to assess the energy required to reach general comfort in the baseline case. The heating and cooling setpoint temperatures were set to the Passivhaus EnerPHit standard comfort temperature requirements of 20ºC and 25ºC, respectively. The predicted DesignBuilder baseline model energy consumption was, unsurprisingly, much higher than the EnerPHit standard required value due to the very poor envelope insulation. Figure 3-15 and Figure 3-16 display the simulated yearly and monthly energy consumption of the baseline model. Because the lighting and household equipment were only included in simulation for their heat gains to the indoor environment, and their setting in DesignBuilder kept the same before and after retrofitting, only energy consumption for heating and cooling were considered in the study. The predicted annual heating demand of 150.6 kWh/m^2a, was more than seven times the Passivhaus standard value, while the predicted annual cooling demand of 42 kWh/m^2a, was about three times the required value. This illustrates that heating is the dominant energy consumer in this climate for these types of dwellings and that the energy-saving possibilities for heating through a deep energy retrofitting are much higher than for cooling. The DesignBuilder simulated energy consumption of the baseline model was very different with the actual yearly recorded electricity consumption of 4345 kWh, which equal to 44 kWh/m^2a. This was because the baseline model was assumed to be heated and cooled to a relatively comfort level and the case building in fact was mostly not actively heated and cooled. However, the monthly electricity bill of the case building showed the consumption in winter and summer months would be significantly higher without efficiently improving the indoor thermal environment due to the poor envelope thermal performance. This also suggested a deep retrofitting could be meaningful for both thermal comfort and energy savings.

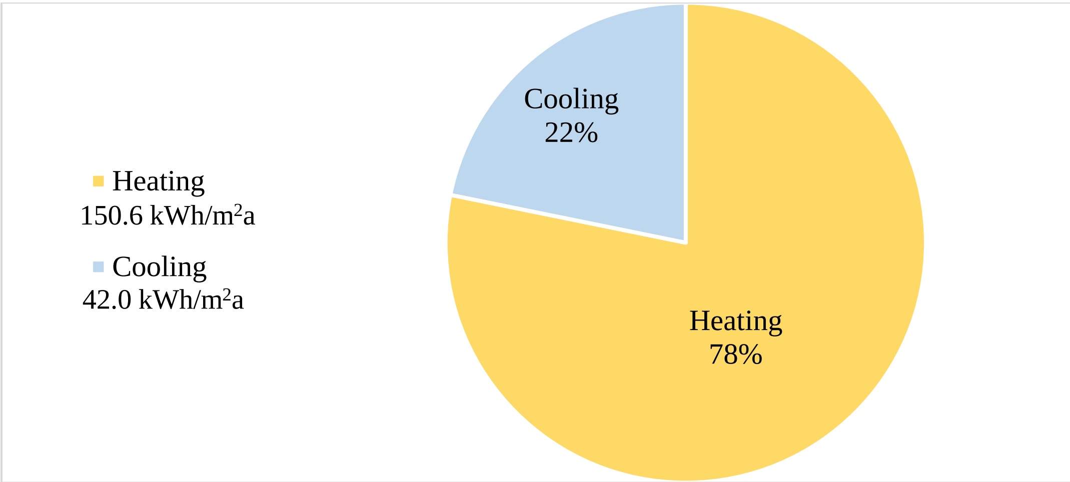


Figure 3-15: Yearly energy consumption of the baseline model.

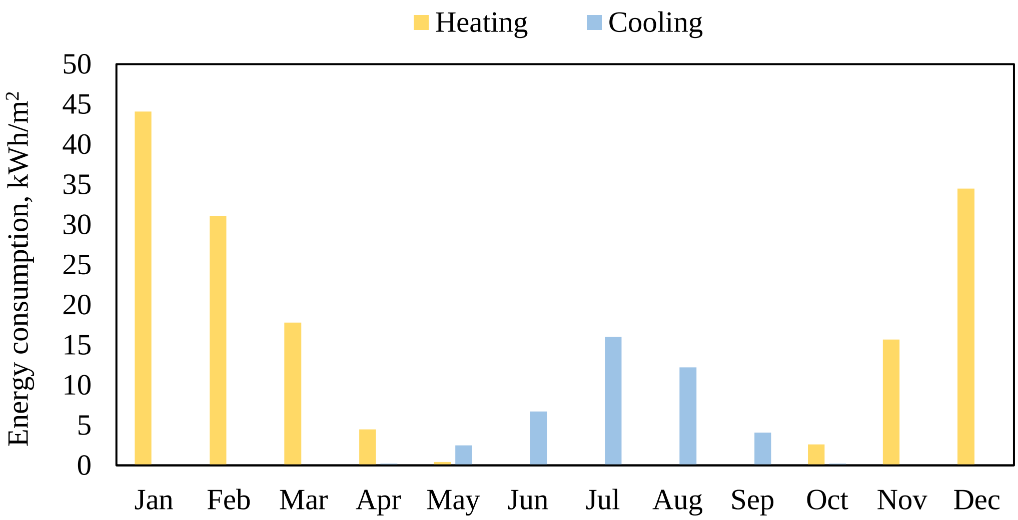


Figure 3-16: Monthly energy consumption of the baseline model.

3.9. Summary

This chapter began by introducing the case building for the research, then followed with the review of the monitored hygro-thermal data, where a good understanding of the characteristics of the studied hot summer - cold winter climate was established, which helped with deciding the retrofitting strategy to achieve the energy standard aim covered in the next chapter. The monitored data were also used to evaluate the indoor thermal comfort by the adaptive thermal model method, which found that the case building was only in the class I comfort range for around 13% of the year. Thus, a high standard retrofitting could be effective for increasing the indoor comfort to modern standards in this type of dwelling. Furthermore, for establishing a reliable baseline model of the case building for the following retrofitting, a DesignBuilder model was created based on the features of the actual building and calibrated in various ways. In the end, the energy performance of the baseline model was identified based on simulation, which was 150.6 kWh/m^2a for heating and 42.0 kWh/m^2a for cooling. This energy performance will be compared to the retrofitted cases in the following chapters. In the next chapter, a step-by-step retrofitting process is evaluated using the baseline model to discover if the Passivhaus EnerPHit standard was achievable for the case building and the potential energy-savings after the retrofit.

Chapter 4. Retrofitting the baseline house towards the EnerPHit standard

4.1. Overview

The baseline model of the case building was created and calibrated in the simulation software DesignBuilder, as described in the previous chapter. In this chapter the study moves to one of the main aspects of this research, which seeks to discover the possibility that the baseline model can be virtually retrofitted towards the Passivhaus EnerPHit energy standard of 20 kWh/m^2a and 15 kWh/m^2a for active heating and cooling respectively. Because the active heating was found to be the dominant source of energy consumption, when previously evaluating the baseline energy performance, more attention was paid to the decision of the retrofitting measures adopted to the baseline model to minimise the heating energy than the cooling energy. For example, experience from Passivhaus projects built in a similar climate with the case building, reviewed in Chapter 2, suggested that a thick layer of insulation material should be applied to the building envelope to achieve the EnerPHit standard required heating target. The primary aim when deciding the retrofitting strategies was to achieve the overall energy goal, balance the retrofitting's efforts to energy-saving between heating and cooling, and, finally, to optimise the retrofitting plan as the last research stage. This chapter introduces the overall retrofitting strategies before presenting a detailed step by step retrofitting simulation process in DesignBuilder. The corresponding reduction in energy consumption required by the case building in each retrofitting step is discussed in detail. After this, in the retrofitting summary section, the energy performances of the pre-retrofit and retrofitted cases were compared against the EnerPHit standard to assess the improvement. Finally, the same retrofitting plan was simulated in PHPP to verify the retrofitting efficiency.

4.2. Retrofitting strategy

The first aim of this chapter was to explore whether the case building could manage to achieve the strict Passivhaus EnerPHit standard under the hot summer - cold winter climate. All the simulations of the considered retrofitting measures were applied to the baseline model to evaluate their effects on the building's energy performance. The DesignBuilder assumptions for retrofitting simulations regarding heating and cooling set temperature, occupants' metabolic rate and activity schedule, and household equipment were all kept the same with the baseline model, so the effects of the retrofitting measures were examined under the same interior casual heat gain conditions. The only change was that the original low standard lighting was replaced with LED lighting, which has a lower energy density (Table 3-7) and, therefore, the interior heat input from lighting in the retrofitted case was simulated as 7.6 kWh/m^{2}a lower than the baseline case.

Building design parameters such as orientation, window-to-wall ratio and shape factor, are classified as geometrical factors with a strong relationship with natural lighting, ventilation and solar heat. Thus, these factors should be carefully considered at the design stage of an energy-efficient building to take advantage of the external situation (X. Chen, Yang, & Lu, 2015). Building design regulations over the world also have recommended values for those design parameters; for the study's climate zone, the recommended orientations for a living space is facing south or within 15^o east or west of south; the window to wall ratio should not exceed 0.45 and 0.4 for south and north façades, and not over 0.35 for both west and east façades; and the shape factor should not exceed 0.4 (*DBJ 43/001-2017*; MOHURD, 2010). For the case building, however, the orientation is towards the east and totally outside of the recommended range; the window to wall ratios for exterior east and west facades are 0.35 and 0.31 respectively, and the shape factor is 0.33, and so those two parameters are in line with the guideline. When considering the practical feasibility of retrofitting, it is not possible to change the orientation and shape factor of the case building, and the size of the exterior windows is within a relative good value, so therefore it was decided that the original architectural design features should be maintained in the retrofitting process, although they may increase the challenge to achieve the EnerPHit energy goal.

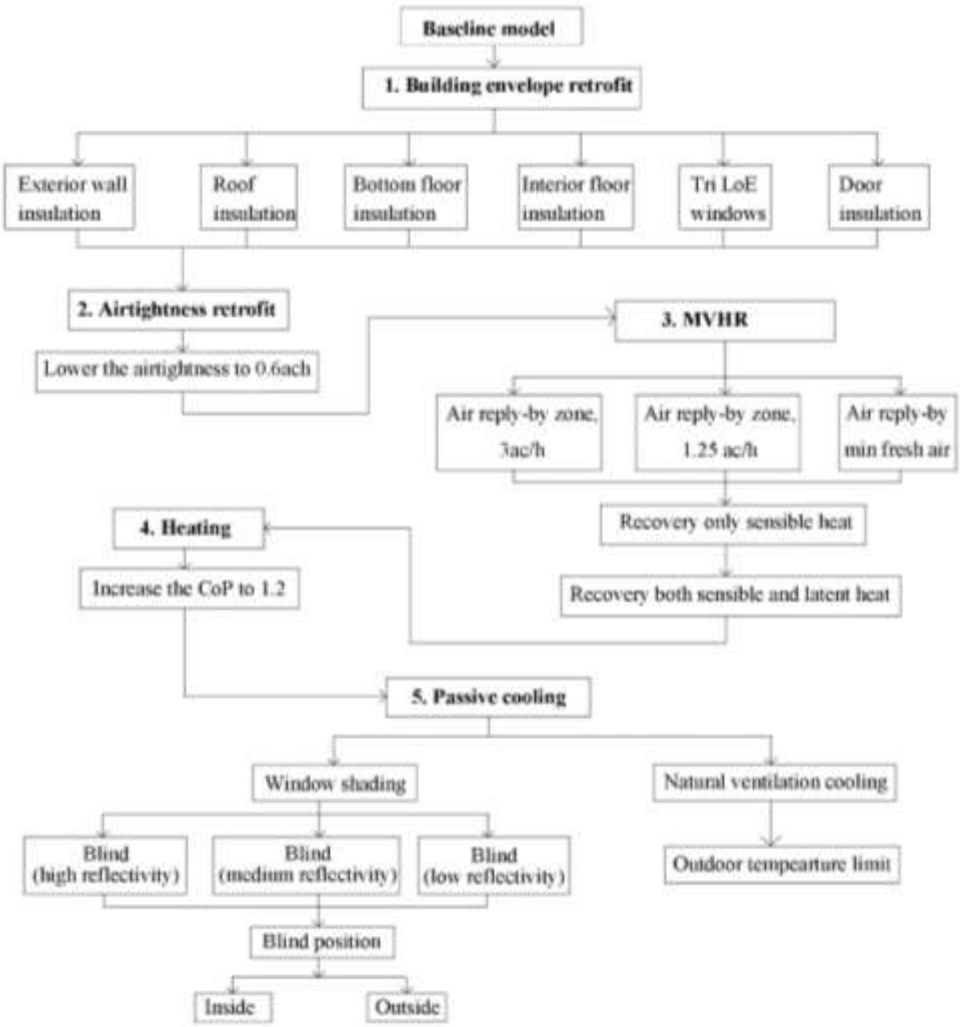


Figure 4-1: Summary of the retrofitting process.

The first aim of this research was to explore whether the case building could achieve the strict Passivhaus EnerPHit standard under the hot summer - cold winter climate. Following the Passivhaus standard, the concept of a 'fabric first' approach, which prioritises heat retention and reduces air leakage, followed by using an efficient heating and ventilation system, was applied to the retrofitting. A summary of all the retrofitting measures applied to the baseline model is given in Figure 4-1.

A series of numerical simulations were carried out to quantify how the required heating and cooling energy consumption levels in the building decrease following the retrofit steps and eventually meets the EnerPHit standard requirements. The entire retrofitting process was divided into five core phases, which began with improving the building envelope insulation performance. After considering the feasibility of the retrofitting strategies, internal (rather than external) fabric insulation was selected. Due to the West-East orientation and narrow shape of the building, and considering the practical examples of the Passivhaus in hot summer - cold winter climate areas, it was decided to use a 250mm thickness of Rockwool insulation for the whole envelope. The single glazed windows were replaced with triple glazed windows, which have a similar thermal performance as with the Passivhaus buildings in China. In the second phase, the airtightness level of the baseline model was assumed to be improved from 3.0 ach to a superior value of 0.6 ach. In the third phase, a mechanical ventilation system with a sensible and enthalpy heat recovery function (MVHR) was modelled. Several settings that provided fresh air and different heat recovery efficiencies were simulated to find the best setting for energy savings. Considering Hunan's humid and cold weather condition, this system provided fresh air almost all year round and robustly assisted the heating supply in winter. Furthermore, the heating system's coefficient of performance (CoP) was slightly improved for better heating energy performance, while the cooling system's setting was kept the same as the baseline model as active cooling was necessary under the hot summer – cold winter climate. In the end, additional passive cooling using shading and ventilation cooling were adopted for further cooling energy reduction and, finally, the model achieved the EnerPHit standard for cooling energy demand.

4.3. Building envelope retrofitting

The building envelope includes the total building surfaces that separate the outdoor and indoor environment, and it controls the heat flows in between and plays an important role in the building's thermal and energy performance (Oral, Yener, & Bayazit, 2004). The building envelope is also physically responsive to the climate condition; a climate-responding envelope design could take advantage of positive climate attributes to enhance building energy efficiency (Hu & Yu, 2019). Therefore, for the case building in this research, the envelope heat balance towards the outdoor environment was examined based on the simulation of the baseline model before any retrofitting measure took place. Overall, exterior walls and windows were the main envelope components that disseminated indoor heat sources to the outdoor environment, though the area of the windows is only around 13.8% of the area of external walls. They take up 53% and 25% of the total envelope heat loss of 23869 kWh, respectively, with roof, and interior floors account for 9% and 12% of the total amount. Figure 4-2 (a) demonstrates monthly heat flows of each of the envelope components and, unsurprisingly, all of the components had heat loss from indoors in winter months. It should also be noted that the exterior walls and roof gain a certain amount of unwanted heat from the outdoor environment in summer time.

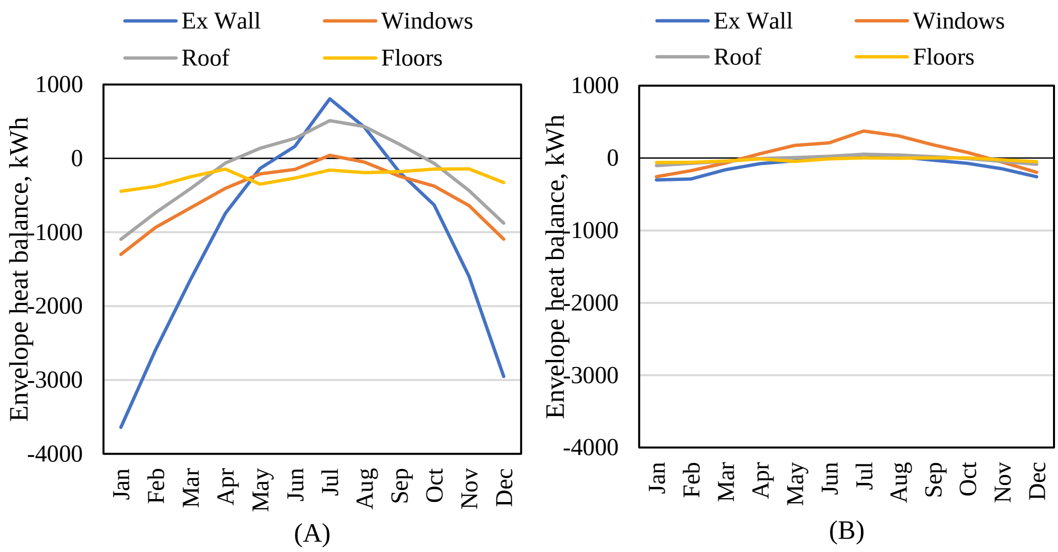


Figure 4-2: (a) Baseline model envelope heat balance from indoor to outdoor; (b) Insulated envelope heat balance from indoor to outdoor.

Once the baseline thermal performance was understood, the retrofitting of the case building commenced, with improving the insulation performance of the envelope involving incrementally applying insulation material to the outside wall, roof and floors, followed by the replacement of the exterior windows and doors. A commonly used and affordable insulation material in China is Rockwool, which has a density of 100 kg/m^3 and thermal conductivity of 0.033 W/mK, was applied to the baseline model. Given that the overall heat loss from the baseline envelope was significantly more than the heat gain, an insulation thickness of 250mm was selected. If this level of insulation material is placed on the inner side of the envelope, it should result in a loss in interior space. However, exterior insulation is not suitable in this case because of the restriction from the existing semi-detached construction. The aerogel insulation is a newly developed material that is able to achieve interior insulation without loss of interior space because it has a much lower thermal conductivity (around 0.020 W/mK) than traditional materials and therefore the same insulation performance could be achieved with a much thinner layer of insulation (Yin et al., 2022). This material was not considered in this study because it is rarely applied in the studied region and could not reflect reality. The detail of the envelope's thermal performance after applying insulation material is shown in Table 4-1. The 'first floor' is the lowest level of the retrofitting space because only the residential areas on the top three floors of the building have been considered to be retrofit. Figure 4-3 shows the comparison of total envelope heat gain/loss between the baseline and insulated case, where a reduction of 94% in total heat loss was observed compared with the baseline case.

Table 4-1: Building envelope retrofit and the U-values

	Insulation material	Insulation thickness	U-value before Retrofit (W/m^{2}K)	U-value after Retrofit (W/m^{2}K)
Walls	Rockwool	250mm	2.30	0.125
Roof	Rockwool	250mm	1.76	0.123
First floor	Rockwool	250mm	2.85	0.126
Interior floors	Rockwool	250mm	2.85	0.126
Glazing	Triple glazing LoE		5.85	0.78
Doors			2.82	0.833

Moreover, from the monthly envelope heat balance of the insulated case, as shown in Figure 4-2 (b), it is worth noting that the unwanted heat gain absorbed by the exterior wall and roof was relatively small in each of the summer months (below 50 kWh) after the insulation was modelled, thus sufficient insulation improved the thermal performance of these two opaque envelope components in both winter and summer time under the hot summer–cold winter climate context. On the contrary, compared with the baseline single glazed windows, the retrofitted triple glazed LoE windows reduced heat loss from indoors in winter by a large amount but had a significant heat gain in summer. This suggests that additional measures were required to decrease the heat gain from windows in the following retrofitting process in order to minimise the required energy consumption for cooling. Once the envelope fabric heat balance between indoor and outdoor environment had been analysed, the next step was the simulation of how the heating and cooling demand in the building progressively changed with the different stages of the envelope insulation retrofitting, and the results are summarised in Figure 4-4. Figure 4-4 shows the cumulative effects from the measures in this retrofitting phase, in which the energy consumption changes from retrofitting measures including the measures applied before this one. The individual effects of the retrofitting measures were displayed in Figure 6-13 in Chapter 6, which demonstrated that the energy saving effect from each individual measure was quite limited when targeted at a high retrofitting standard.

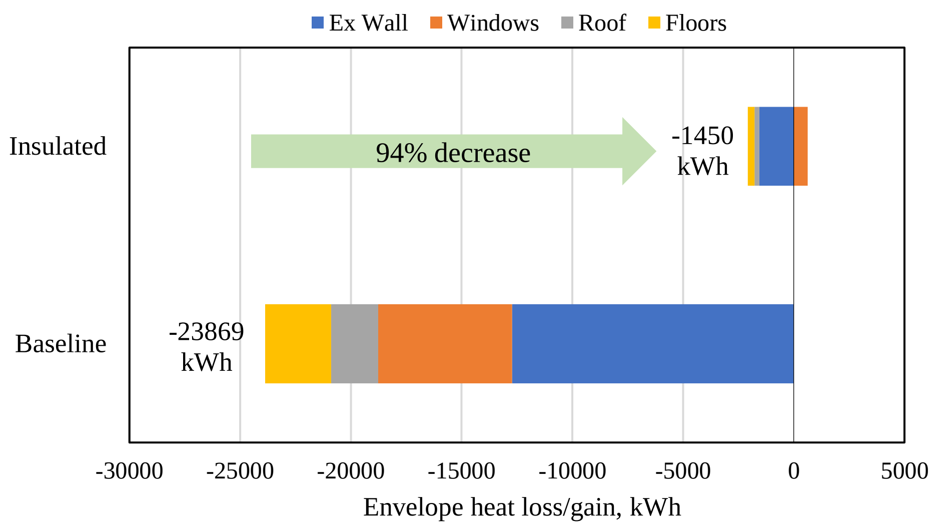


Figure 4-3: Fabric heat loss/gain before and after envelope insulation retrofit

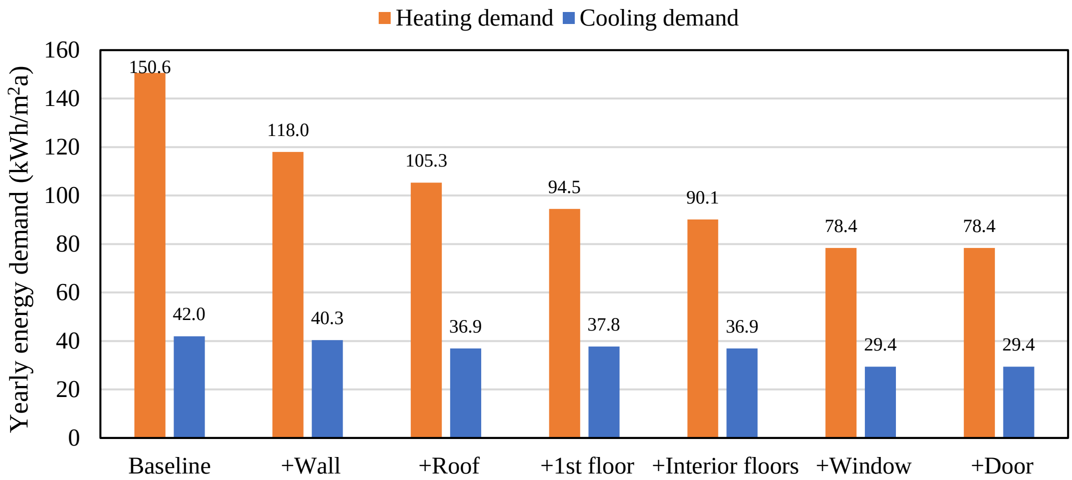


Figure 4-4: Annual heating and cooling energy demand changes under the cumulative effects of each of the measures in phase 1 building envelope retrofitting.

In terms of energy saved by retrofitting, on the heating side, 48% of energy is saved from the whole envelope insulation. More specifically, the wall insulation was the most efficient measure applied, as it decreased the yearly demand to 118 kWh/m^{2}a from the baseline value of 150.6 kWh/m^{2}a. Both the roof insulation and first floor insulation each contributed around 10 kWh/m^{2}a of energy saving, bringing the demand down to 94.5 kWh/m^{2}a. Then, the insulation was applied on the interior floor as well, as interior floors are insulated in real world Passivhaus projects in the study climate area. This gave a further energy reduction of 4.5 kWh/m^{2}a. Next, the single glazed windows were replaced with triple low emissivity (LoE) argon filled glazing, which lowered the demand to 78.4 kWh/m^{2}a. On the cooling demand side, the energy demand showed a less significant decrease over the whole envelope insulation retrofit process, from 42 kWh/m^{2}a to 29.4 kWh/m^{2}a (a 30% reduction). The factor that contributed most to the cooling energy reduction were the high-performance windows, which lowered the value by about 6 kWh/m^{2}a. The interior floor insulation increased the interior heat gain in the summertime, and the cooling demand was enhanced for 1 kWh/m^{2}a. Furthermore, both the heating and cooling demand remained the same after fitting the three new flat entrance doors with a lower U-value of 0.833 - this could be because they face the staircase, which is a semi-exposed space rather than an outside environment. From simulations of step by step insulation of the envelope, it was observed that the heating energy consumption of the building was very sensitive to the degree of the whole envelope insulation, while its influence on the cooling energy was more sensitive to the transparent envelope. The overall results suggest that the first stage of retrofitting involving insulating the whole envelope significantly improved the energy performance of the case building but that further retrofitting measures were required to meet the EnerPHit energy criteria.

4.4. Building airtightness retrofitting

The airtightness performance is another critical factor that can result in significant heat loss from an indoor environment, which may cause uncomfortable air temperature fluctuation and a reduction in energy efficiency (Gillott et al., 2016). The uncontrolled air movement between the indoor and outdoor environment through leakages or gaps in the building envelope is defined as infiltration, representing a building's airtightness performance (Sadineni, Madala, & Boehm, 2011). Many characteristics influence the airtightness performance of an existing building, such as structure type, construction and age of building, floor area and storeys numbers, and so it is necessary to measure the accurate infiltration rate of a specific building by a blower door test (Montoya, Pastor, Carrié, Guyot, & Planas, 2010).

The exact infiltration rate for the building in this case study could not be measured and was therefore assumed to be 3 ach based on the baseline model calibration simulations presented in section 3.7. The EnerPHit standards required an airtightness level of no more than 1.0 ach. However, results from assessments of Chinese Passivhaus projects suggested an infiltration rate of 0.6 ach or even lower was necessary to achieve the strict Passivhaus energy criteria. Moreover, simulation results show that, for the case building with an infiltration rate of 1.0 ach, the energy consumption required by the EnerPHit standard was not reached even after all the retrofitting measures, described in the following sections, were applied. Therefore, it was decided that an infiltration rate of 0.6 ach should be adopted in this stage of retrofitting, while values lower than 0.6 ach were not considered because airtight envelope is more difficult to achieve in retrofitting projects than new builds.

Skilled and careful construction is necessary to attain a low envelope airtight level like 0.6 ach. For example, the exterior windows should be placed next to the wall insulation layer, and the air leakage protection membrane should be applied on the interior side where the windows and walls are connected in order to cut off the air leakage and thermal bridge during construction. This was done for the a Passivhaus in China (*Passive windows*), which also used tape both inside and outside of the windows-wall conjunction to ensure a very low airtightness value could be achieved (Figure 4-5). The connections between two different envelope components, such as wall masonry joints with a structural beam, should be fully glued with a vapour barrier membrane to ensure the airtightness between the masonry and concrete structure. Inevitable penetrating parts, such as pipes that go through the envelope, need to be sealed by tape or foam caulk (China Building Energy Association, 2019). Therefore, an uninterrupted airtight layer can be formed inside the envelope to achieve a good airtightness performance.

Figure 4-5: Air leakage protection membrane used on both inside (left) and outside (right) of the window in a Passivhaus in Hunan, China.

In DesignBuilder simulations, construction details like using tape or foam caulk to fill the gaps between conjunctions were not able to be modelled. In this step of retrofitting, the infiltration rate of the DesignBuilder model was changed from the baseline of 3 ach to an excellent level of 0.6 ach to assume an airtight envelope was achieved. Accordingly, the yearly heat loss from the indoor environment through infiltration was dramatically lowered from 20923 kWh to 5573 kWh, a 73% decrease, and thus resulted in a considerable saving in the required energy consumption in the case building. As shown in Figure 4-6, the required heating consumption reduced dramatically from 78.4 kWh/m^{2}a to 17.3 kWh/m^{2}a, which achieved a 78% energy saving from the last retrofitting phase. In addition, 22% of energy saving was also achieved on the cooling side, as the energy demand was reduced to 22.8 kWh/m^{2}a from 29.4 kWh/m^{2}a in the last retrofitting phase. The results show that lowering the airtightness level is a highly efficient measure for energy saving and that the resulting heating demand had reached the EnerPHit standard. However, before and during this phase, natural ventilation was incorporated within the model to supply the minimum fresh air the occupants need, and windows were controlled by the schedules which depended on the function and activity of each room, which leads to a serious risk of poor indoor air quality during the time the windows are closed, like sleeping time. This risk was addressed in the next retrofitting measure.

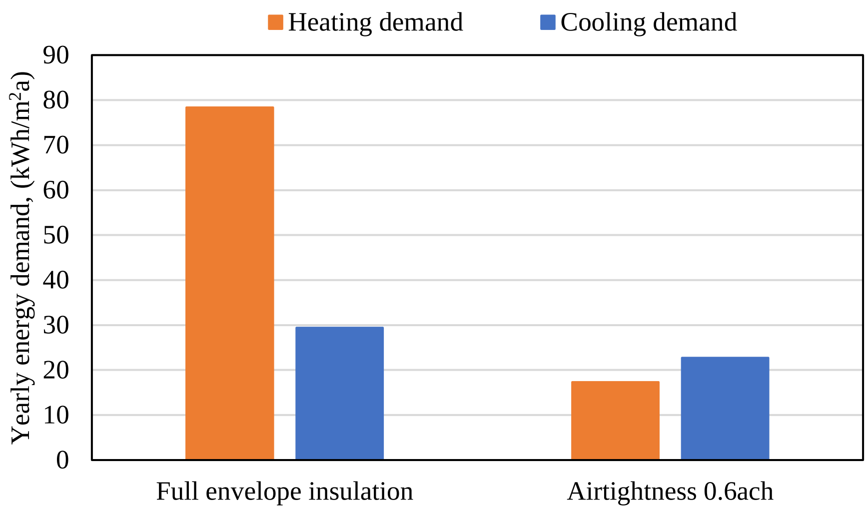


Figure 4-6: Comparison of energy demand between phase 1 and phase 2 of the airtightness retrofitting.

4.5. Mechanical ventilation with heat recovery (MVHR) system

One of the most important Passivhaus concepts is the aim to make the best use of heat sources inside the building, such as heat released from lighting, household equipment and occupants, which are well retained by the super-insulated and airtight envelope, thus the required energy consumption for active heating could be minimised. To utilise the useful indoor heat sources, the exterior windows and doors are mostly kept shut, resulting in a poor indoor air quality problem, as identified in the previous section. Therefore, the utilisation of a mechanical ventilation system with heat recovery function is deemed to be necessary for bringing the fresh air in and recovering the indoor heat sources.

During this phase of the retrofitting, a mechanical ventilation system with a heat recovery function based on an actual product produced in China was modelled to ensure healthy indoor air quality and to recover the internal heat gain. Figure 4-7 shows the actual MVHR system, which is a Passivhaus Institute (PHI) certified product and manufactured by the Chinese company Zhongshan Wonderful Electronic Thermal Control Technology Co., Ltd. This MVHR system can recover both sensible heat and enthalpy heat, with a recovery efficiency of 85% and 80%, respectively. The sensible method recovered the heat from the exhaust air, and the enthalpy method involves both sensible and latent heat recovery, where the supply temperature and humidity ratio are both affected by the indoor exhaust air. This system is among the products with the best heat recovery performance in the Chinese market and, therefore, was selected for case building retrofitting. The selected MVHR system can supply air to an area up to 300 m^2 and, as the total treated floor area of the three flats in case building was 228 m^2, one system was simulated for the whole building.

Figure 4-7: Photo of the cited MVHR system

Typically, a well-designed Passivhaus adapted to a European climate requires an MVHR system with only sensible heat recovery function, and the efficiency should be over 75% to sufficiently recover the indoor heat (Schnieders & Hermelink, 2006a). However, the studied hot summer – cold winter climate commonly has a high relative humidity level all year round. As per the field measurement result shown in Section 3.2, the monthly mean outdoor relative humidity level was between 69% and 89% during the recorded one-year time, and the indoor humidity was very close with the outdoor situation. An MVHR system that recovers both sensible and latent heat would decrease the humidity level of the inside air and hence improve the indoor thermal comfort. To verify the effect of the latent heat recovery function of the MVHR system, the building's energy performance was investigated under the studied climate type. The DesignBuilder model with the first two stages retrofitting measures simulated an MVHR system with i) only 85% sensible heat recovery, and ii) both 85% sensible and 80% latent heat recovery. In addition, the amount of fresh air induced into the indoor space affected the heat loss caused by ventilation and, thereby, the energy consumption (Schnieders & Hermelink, 2006b). Therefore, three outside air supply scenarios were tested for the mechanical ventilation system in order to balance the indoor fresh air and ventilation heat loss. The scenarios involved, firstly, a fresh air delivery rate of 3ac/h; secondly a delivery rate of 1.25 ac/h; and thirdly the minimum fresh air required per person. Figure 4-8 represents the simulated heating and cooling energy demands when the MNHR system operates with those three scenarios under different heat recovery method.

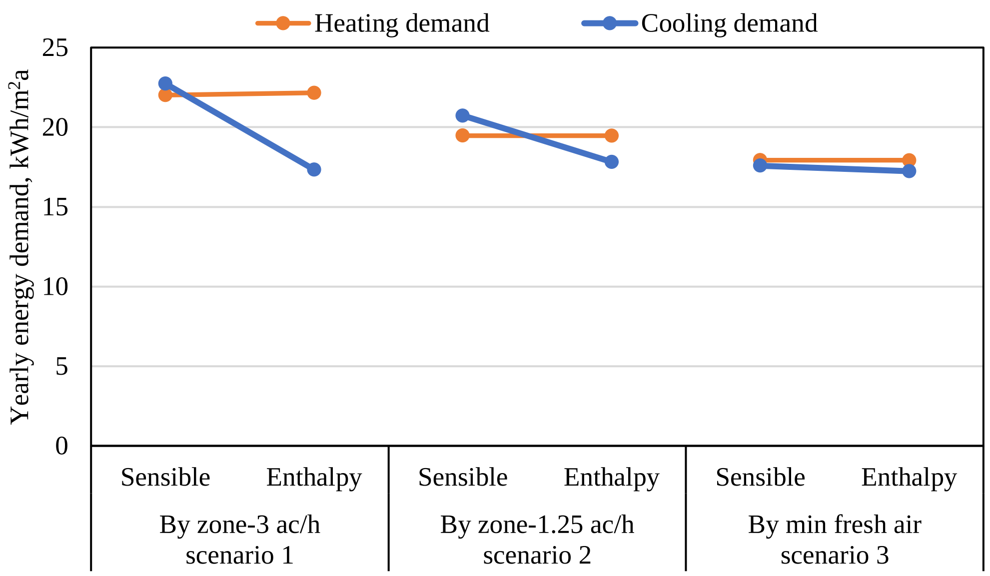


Figure 4-8: Comparison of energy demand under three mechanical ventilation system scenarios.

As shown in Figure 4-8, the first group of results were derived from when the ventilation system supplied the fresh air depending on the indoor zone size and with a delivery rate equivalent to 3 ac/h. The heating and cooling demands were 22.0 kWh/m^{2}a and 22.7 kWh/m^{2}a respectively when the sensible heat recovery method was used, while when operating with the enthalpy method, the cooling demand went down to 17.3 kWh/m^{2}a, and the heating demand remained the same. The second group of results were determined by the zone size as well, but with the outside air delivery rate lowered to the equivalent of 1.25 ac/h. In this scenario, the heating demand was reduced to 19.5 kWh/m^{2}a, and the cooling demand was 17.8 kWh/m^{2}a when using the enthalpy method, which was 3 kWh/m^{2}a lower than in the case of the sensible method value of 20.7kWh/m^{2}a. Next, the third group of results show the scenario with the mechanical ventilation system suppling fresh air determined by the minimum fresh air requirements for the occupants. The energy demand was now the lowest among the three scenarios - the heating demand was 17.9 kWh/m^{2}a for both heat recovery methods, and the cooling demand was slightly lower when the enthalpy method was used, which is 17.2 kWh/m^{2}a.

In summary, the enthalpy heat recovery method was a more suitable retrofitting measure for the studied climate, as the enthalpy heat recovery method neutralised the relatively wet outdoor supply air and dry indoor exhaust air, which contributed to a lower energy consumption for cooling. Scenario 3 of the MVHR system was the method which delivered the lowest amount of fresh air of the three examined scenarios, and the DesignBuilder default setting for average minimum fresh air per person in a residential space was 10 l/s (equal to 36 m^3/h), which was in line with the Passivhaus standard required lowest fresh air amount of 30 m^3/h for each person. Also, scenario 3 demonstrated the best energy performance, whether the system recovered heat by sensible method or enthalpy method as the ventilation heat loss was the smallest under this scenario. However, scenario 3 with the enthalpy heat recovery method of the MVHR system was rolled into the next retrofitting step because the cooling energy consumption was slightly lower.

4.6. Heating system efficiency

Because the heat losses from building fabric and ventilation are largely prevented, the heating requirement is minimal and the demand for conventional heating system is small in many European Passivhaus examples (McGill, Qin, & Oyedele, 2014; Schnieders & Hermelink, 2006a). To check if the heating system was required under the studied climate context when the case building had the above-mentioned retrofitting measures all attached, the heating system in the DesignBuilder model was turned off to determine the situation of indoor thermal comfort. Figure 4-9 shows the difference in indoor daily mean temperature during January (the coldest month) when the heating system was in operation and when it was turned off. When the heating system was set off, the indoor air temperature varied between 8.5 ºC to 15 ºC, which was not considered comfortable. Comparatively, the indoor temperature was more comfortable when the heating system was in operation, at around 19 ºC over the whole month. A similar difference was found in other winter months and, therefore, it was determined that the heating system was necessary to support indoor thermal comfort in the case building.

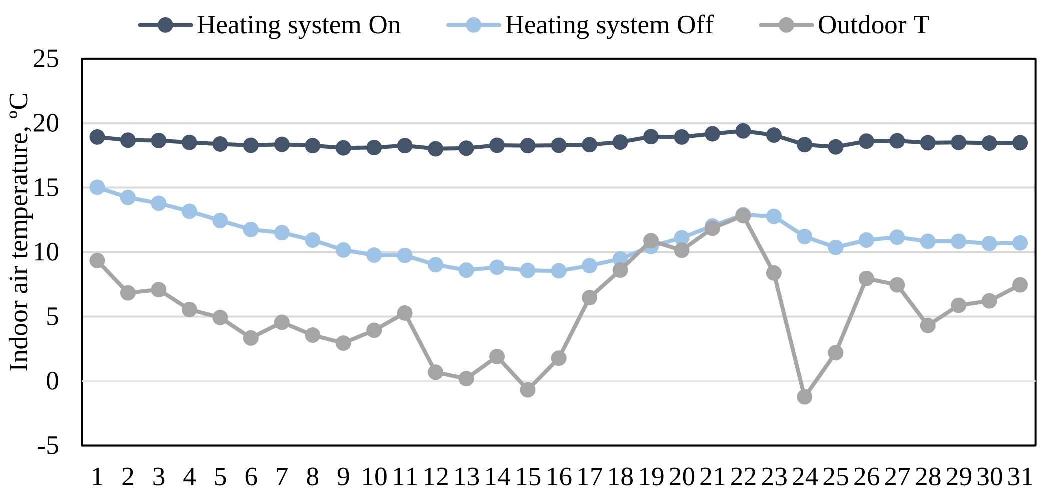


Figure 4-9: Difference in January indoor temperature for heating system on and off.

In Hunan province, the air conditioning system usually has both a cooling and heating supply function because of the dual requirements in hot summer – cold winter climate condition. Thus, in this step of retrofitting, the previously used radiator system with a heating CoP of 1.0 in the baseline model was changed to an air conditioning system with a heating CoP of 1.2, so the system supply both heating and cooling for case building and the heating efficiency could be improved. Figure 4-10 represents the energy demand of the case building after the heating system was improved. The heating consumption was decreased to 14.9 kWh/m^{2}a, from 17.9 kWh/m^{2}a, when the case building had applied MVHR system in the last retrofitting stage, where an energy saving of 17% was achieved. The cooling demand remained the same as the setting for the cooling system was not changed. Overall, the case building's energy performance after the four stages of retrofits was largely improved compared with the baseline performance. However, the cooling demand still did not meet the EnerPHit standard required 15 kWh/m^{2}a. In the next section, passive cooling methods will be analysed to explore the possibility of decreasing the cooling demand.

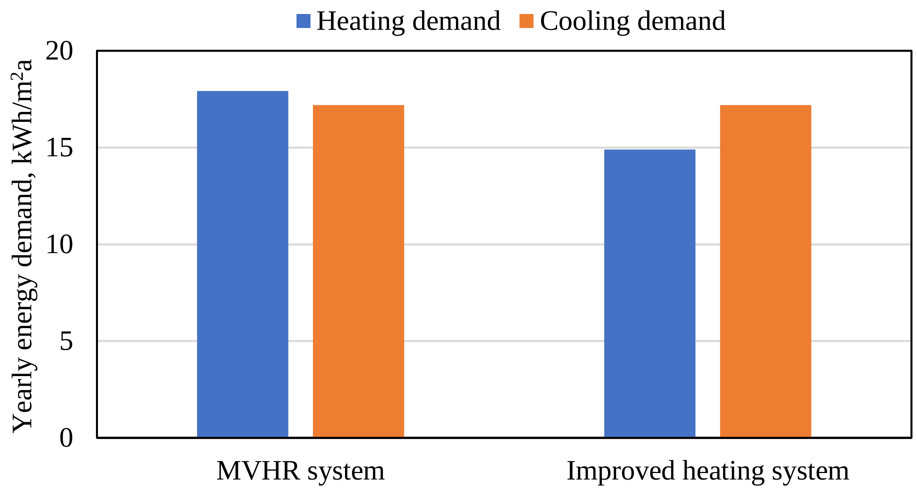


Figure 4-10: Energy demand after improving the heating system

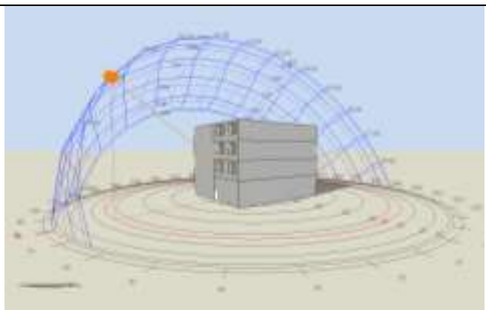
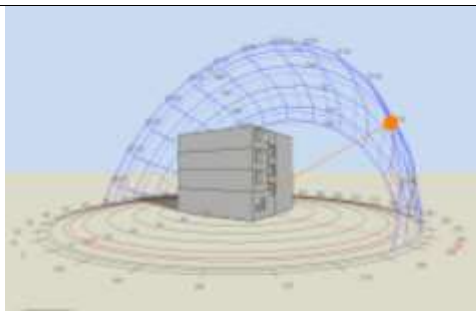
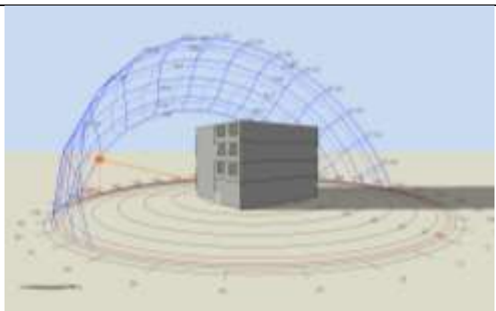
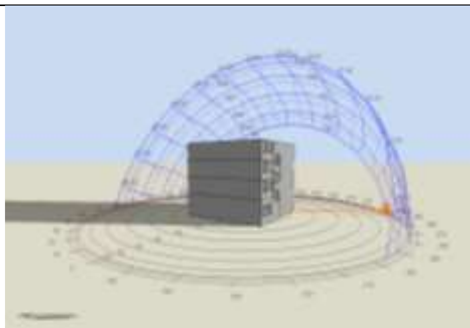
4.7. Passive cooling measures

4.7.1. Window shading

Sun shading is one of the most commonly used passive cooling methods because of its effect on several important building performance areas, including thermal comfort, energy conservation, and visual comfort (Maleki, 2011). Sun shading works simply by blocking the sun's heat from getting into the building, and exterior windows are the weakest part of the envelope to receive excessive sun heat. In Passivhaus, sun shading systems are usually activated during summer months to prevent unwanted solar gain, while they are not activated outside of summer in order to permit solar gain to warm the indoor environment (Kuhn, Bühler, & Platzer, 2001). It has been found that the shading of west and south facing windows is efficient and necessary to limit the interior heat gain as well as maintaining the indoor temperature in hot continental climates (Mlakar & Štrancar, 2011a). For the case building, all windows are facing west and east apart from the windows on the south façade which faces the light well. For the windows facing the light well, it was decided not to apply sun shading because the light well is a deep narrow space that prevented direct sunlight. Moreover, previous findings indicated that high-performance windows adopted in the envelope retrofitting stage, which was initially considered to prevent indoor heat loss in the winter, had a side effect that received a certain amount of unwanted solar gain through the windows (Figure 4-3). Therefore, sun shading of the windows was considered as a potential measure to reduce the cooling energy consumption in the case building.

The type of solar shading devices most commonly used in buildings include overhang, blinds, side fins and automatic self-shading devices, and the selection of shading devices depends on the location, orientation and window characteristics of the building (Bellia, Marino, Minichiello, & Pedace, 2014). Table 4-2 shows the sun movement toward the case building from 8.00 am to 5.00 pm in the summer and winter solstice days. The sun path diagram illustrates that both overhang and side fins were inappropriate shading methods in this instance because all of the exterior windows are located on east and west facades. Hence, the overhang cannot shade the windows in the early morning and late afternoon time, and the sunshine is almost directly through the windows in a period of morning and afternoon in the summertime, so that side fins could not block the direct sunshine. Vertical blinds shading was considered for this case because they directly block the sunshine by covering the window and could be easily controlled depending on the sun's movement.

Table 4-2: Sun path diagram of the case building

	8.00 am	5.00 pm
21st Jun	 View of windows on the east facade	 View of windows on the west facade
21st Dec	 View of windows on the east facade	 View of windows on the west facade

As mentioned earlier, solar heat through exterior windows should be avoided in summertime when the building is likely to be overheated. The outdoor monthly mean temperature was used to determine the possibility that the case building would overheat due to the outdoor environment. The required indoor comfort temperature range by the Passivhaus standard is between 20ºC and 25ºC. Solar heat through windows was considered helpful to the indoor environment when the outdoor temperature was lower than 20 ºC; conversely, with the constant indoor heat sources kept in mind, solar gain was likely to cause the indoor environment to become overheated. Figure 4-11 illustrates the outdoor monthly mean temperature of the weather file used for the simulation, with five months between May and September were above 20 ºC. Preventing solar gain through windows during these five months was consequently considered to be necessary to avoid overheating. Figure 4-12 shows the simulated result of the solar gain received by exterior windows, and the months between May and September all had a monthly solar gain of above 500 kWh. Blind shading was modelled during those five months to see how much solar heat could be avoided, and the resulting decrease in cooling consumption.

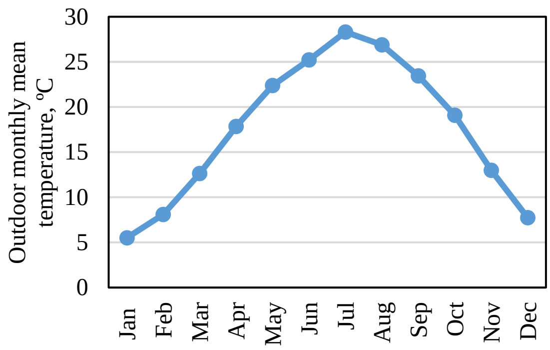


Figure 4-11: Outdoor monthly mean temperature

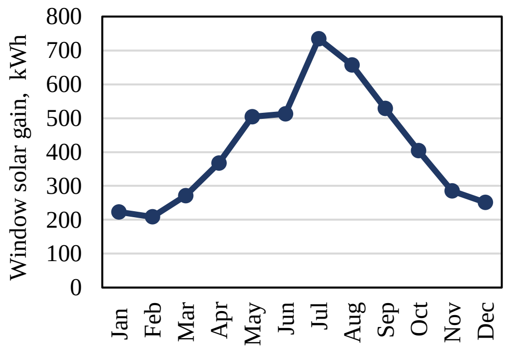


Figure 4-12: Monthly window solar gain

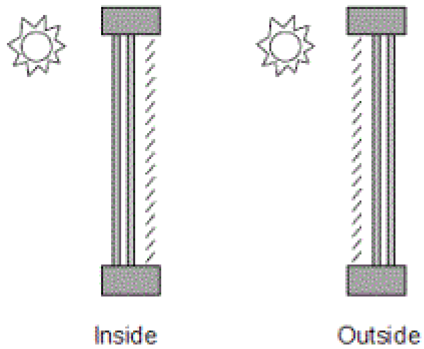


Figure 4-13: Location of the window blinds shading.

Table 4-3: Schedule for window blinds shading operation

From 1 May to 31 September	From 1 October to 31 April
For: weekdays and weekends	For: weekdays and weekends
Until 07:00, 0% operation	Until 24:00, 0% operation
Until 08:00, 25% operation	
Until 09:00, 50% operation	
Until 10:00, 75% operation	
Until 18:00, 100% operation	
Until 19:00, 50% operation	

To check the efficiency of the shading from window blinds on the building cooling demand reduction, three types of window blinds with different slat solar reflectivity of high (0.8), medium (0.5) and low (0.2) were modelled on both inside and outside of the exterior windows (Figure 4-13). The window blinds were operated between May to September and their daily schedule is shown in Table 4-3. The inclination of the blinds in operation was decided based on the intensity of solar radiation in a day. The blinds were set in operation around midday, when the windows do not receive direct sunshine, was to block the diffuse solar radiation, as its intensity was quite strong in this location; for example, the weather file suggested that the average diffuse horizontal solar radiation in July was 90.5 kWh/m^2 and the direct normal solar radiation was only slightly higher, 94.4 kWh.m^2.

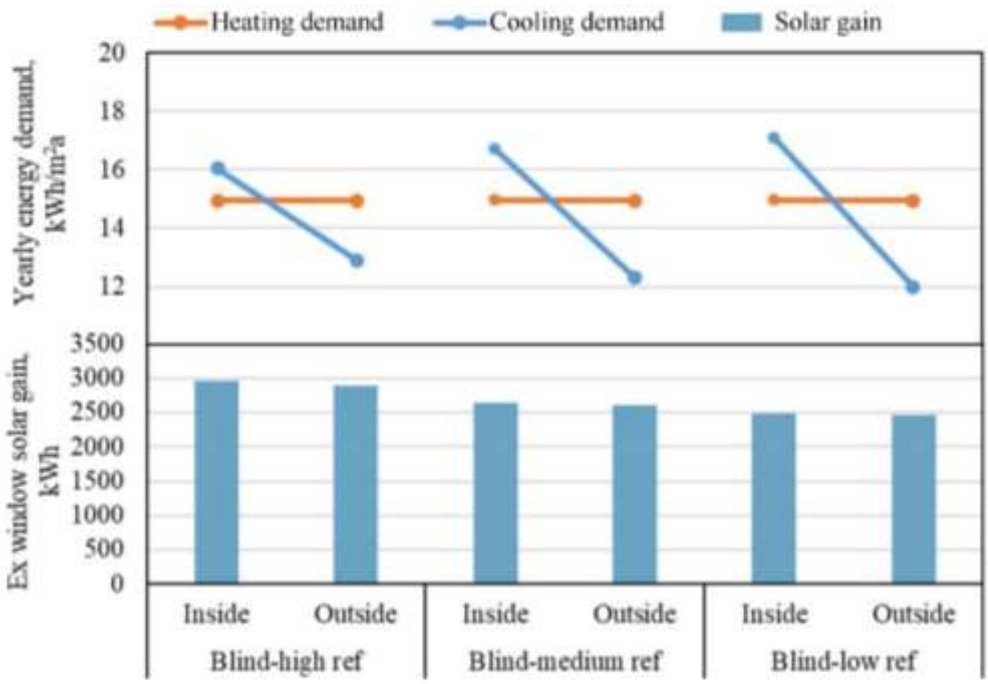


Figure 4-14: Annual energy demand and exterior windows solar gain when blinds with three different solar reflectances were adopted inside and outside the windows.

The simulated result is shown in Figure 4-14, and it suggests that the cooling demand was lower than in the last retrofitting phase (17.2 kWh/m^{2}a) no matter which type of window blinds were applied or placed on which side of the window. The heating demand remained the same as the shading was not active in the winter time. The solar gain from the exterior windows was always lower when the blinds were placed on the outside of the windows, while it was lowest when the blinds had a low solar reflectance. The cooling demand was always lower when the blinds were outside of the windows, and when the blinds have low solar reflectance, the value was lowest, 12.0 kWh/m^{2}a, which is 5.2 kWh/m^{2}a lower than it was in the last retrofitting phase, and the yearly solar gain received by exterior windows decreased from 4959 kWh to 2460 kWh with this shading method. However, it is noteworthy to find that when the blinds were placed on the inside of the window, the cooling demand was lowest when the blinds had a high solar reflectance, while when they were placed on the outside, the cooling demand was lowest when the blinds had a low solar reflectance. This may be because when the blinds are inside the window, the high reflectivity performance helps to reflect the radiation out of the window, so while the heat stored inside the room was lower, the solar gain received by the window was actually higher because the solar heat that was re-reflected back out of the window was also included according to the DesignBuilder manual (DesignBuilder). When the blinds are outside, the low reflection performance reduces the radiation reflected between the slats, and less solar radiation eventually enters the window. In conclusion, the position of the window blinds could cause a significant difference in the cooling demand, and the solar reflectance of the blinds also affects the energy demand. For this study, the solution of placing the blinds with low solar reflectance outside of the windows is adopted because the cooling demand was the lowest.

4.7.2. Natural ventilation

Natural ventilation is also a critical passive method to reduce energy consumption and maintain thermal comfort in Passivhaus design. Night-time natural ventilation cooling helps to reduce the overheating problem in summertime (Artmann, Manz, & Heiselberg, 2008). However, in the hot summer - cold winter climate region, it is essential to keep all the windows closed and only ventilate using the MVHR system in summer. This is because the outdoor temperature is usually much higher than the Passivhaus required upper comfort temperature of 25 °C, even at night-time. During transitional seasons, natural ventilation is still a good way to improve indoor air quality and reduce energy consumption (Yang Wang et al., 2014). Thus, the natural ventilation was activated by outdoor temperature control in the DesignBuilder simulation, which only operated when the outdoor temperature was between the Passivhaus comfort temperature range of 20 °C to 25 °C. So, the natural ventilation method would not increase the heating demand and could assist with passively maintaining the indoor temperature when the outdoor temperature is suitable. Figure 4-15 reveals the annual heating, cooling demand and the heat gain through exterior ventilation after natural ventilation was applied.

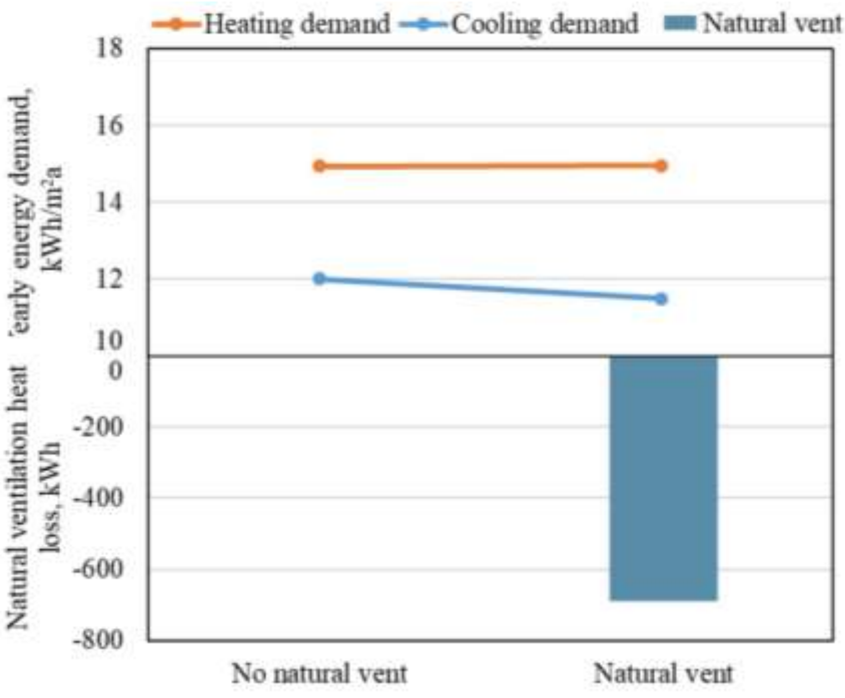


Figure 4-15: Annual energy consumption and heat gain from exterior ventilation before and after the natural ventilation was adopted.

The results show that there was no heat gain/loss from natural ventilation from the last retrofitting step due to the natural ventilation being deactivated. After it was turned on, there was a total annual heat loss of 690 kWh from the building, which led to a cooling demand decrease, from 12.0 kWh/m^{2}a to 11.5 kWh/m^{2}a. The cooling demand did not decrease significantly because the time during which the outdoor temperature was between 20℃ to 25℃ was short in the year - for the outdoor dry bulb temperature shown in Figure 4-16, only around 20% of the time was between this range and mostly in transitional seasons where the cooling demand was low. Overall, the passive natural ventilation method was adopted in retrofitting as it slightly decreased the cooling energy consumption of the case building.

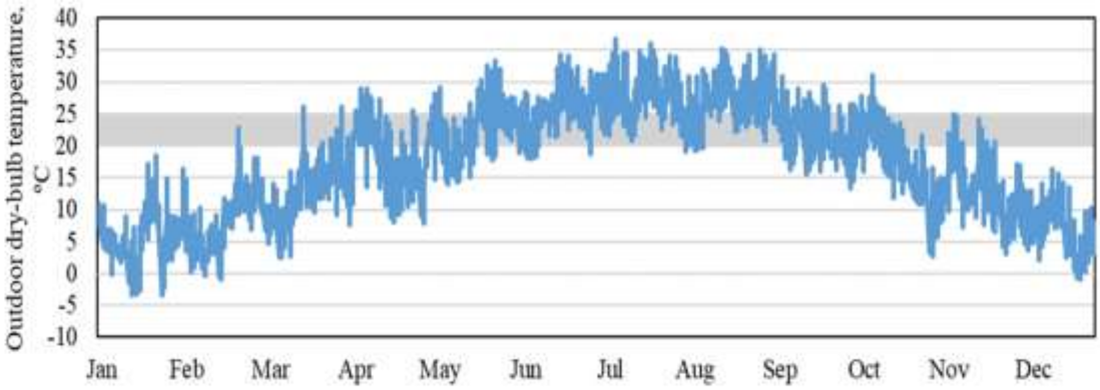


Figure 4-16: Outdoor dry bulb temperature according to Hunan Meteonorm EPW weather file.

4.8. Retrofitting summary

In this study, the results from the field investigation of electricity demand and the pre-retrofit building simulation suggested that the energy consumption for heating was far more than for cooling to keep a relatively comfortable indoor environment. From the retrofitting process, it has been found that all the measures contributed to the achieved energy savings. However, the function of sufficient insulation and a very low air leakage envelope were primary factors for reducing heating energy, while a high level of airtightness, the MVHR system, and passive cooling had a dominant effect on cooling demand reduction. The retrofitting strategies of thick insulation and low air change rates of the envelope were adopted mainly because of the pre-retrofit building's very high heating energy demand. However, the insulation does not efficiently reduce the cooling demand, although the low air change rates (high level of airtightness) could be based on the simulation results. Figure 4-17 summarises the energy demand reductions following the step-by-step retrofitting process. The case building saw a considerable reduction in heating and cooling demand, from 150.6 kWh/m^2a and 42 kWh/m^2a in the pre-retrofitted baseline situation to 14.9 kWh/m^2a and 11.5 kWh/m^2a after retrofitting, energy savings of 90.1% and 72.6%, respectively. The EnerPHit standard requires an energy demand for heating and cooling in this climate area of 20 kWh/m^2a and 15 kWh/m^2a, respectively, therefore, the achieved energy demand for the retrofitted dwelling was 5.1 and 3.5 kWh/m^2a, respectively lower than the criteria values. For comparison, the operational energy demand of a Passivhaus hotel building in this hot summer - cold winter climate area of China was measured, and it achieved 90% energy saving with the heating demand of 15 kWh/m^2a, which is very similar to the simulated results in this study, while the hotel's cooling demand (33 kWh/m^2a) is much higher because higher cooling is needed in hotels and there is a less efficient use of passive cooling measures (Jiangqiu Sui; Yangyang Meng, 2019).

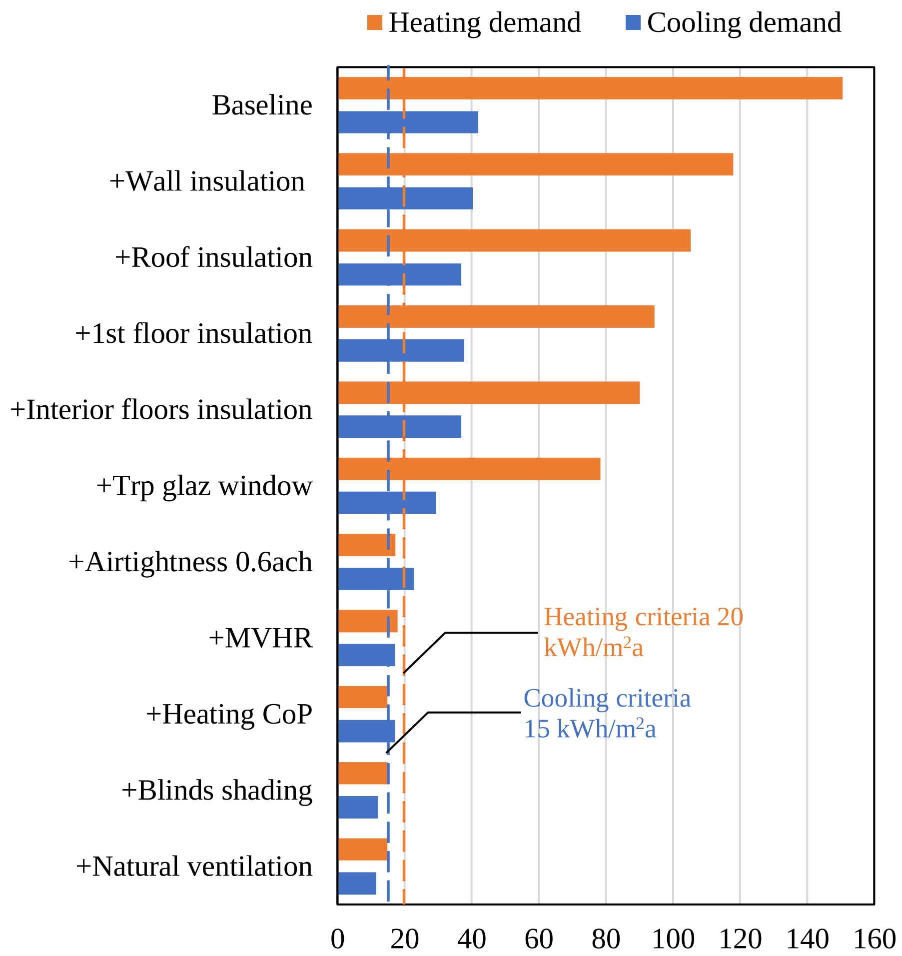


Figure 4-17: The required energy consumption decreases following the retrofitting process.

4.9. Retrofitting through PHPP

In this section, the previously analysed retrofitting measures in DesignBuilder were simulated in Passive House Planning Package (PHPP) software to verify the retrofitting efficiency. PHPP is a Microsoft Excel-based static simulation tool developed by the German Passivhaus Institute (PHI) as a design and certification tool for new buildings and refurbished buildings to achieve the Passivhaus and EnerPHit standards. The accuracy of this tool is based on fundamental laws of building physics, and its calculation procedures have been regularly improved through extensive Passivhaus implementation and new research results from PHI (Müller & Berker, 2013). The energy consumption of a building calculated by PHPP meeting with the standard required value is an integral part of the Passivhaus certification process. Therefore, simulating the energy performance by PHPP was considered as a suitable way of validating the effect of the retrofitting of the studied building.

4.9.1. PHPP inputs

PHPP version 9 was used in this study, which works by a series of Excel worksheets where the necessary information needed for the performance calculation of the objective building is marked in yellow colour, for convenience of the inputs to be filled in or selected from PHPP menus. An interface of PHPP, design PH, was used to build the model of the actual building, so the geometric information was transferred from a 3D model to data inputs which were required by PHPP calculation. To keep the same inputs of the building envelope's insulation performance as in DesignBuilder simulations, the same building materials and insulation material that were applied in the retrofitting process were implemented in the PHPP model. Table 4-4 shows the comparison of U-values of the insulated envelope components calculated by DesignBuilder and PHPP; the slightly different results with the exact same materials (with the same thermal conductive and thickness) could be because of different calculation methods used by the two software packages. For the windows, PHPP could directly select the certified Chinese window product 'Passive 130' from its menu, whereas DesignBuilder selected an argon-filled triple low emissivity (LoE) glazing, which was very close with the window product, the slight difference being in the U-value.

Table 4-4: U-values of the retrofitted envelope calculated by DesignBuilder and PHPP

	PHPP U-value (W/m^2K)	DB U-value (W/m^2K)	Building material detail
exterior walls	0.125	0.125	5mm putty paint, 10mm cement mortar, 180mm clay brick, 250mm Rockwool, 10mm cement mortar, 10mm outside porcelain tiles
Floors	0.127	0.126	10mm porcelain tiles, 250mm Rockwool, 10mm cement, 50mm cement mortar, 100m reinforced concrete raft, 5mm putty paint
Roof	0.125	0.123	50mm cement, 100m reinforced concrete raft, 400mmair gap, 250mm Rockwool, 10mm wood board, 5mm putty paint
Window	0.80	0.78	Triple glazed LoE; Orient-Passive 130 window

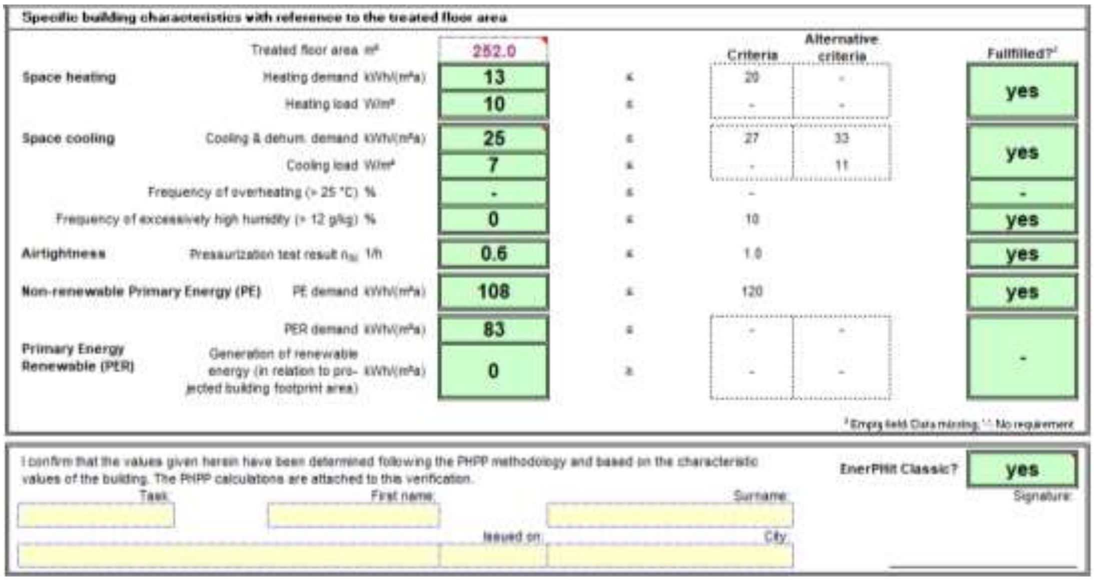
Table 4-5: Building system inputs for PHPP and DesignBuilder.

	PHPP	DesignBuilder
MVHR	Heat recovery efficiency 85% Humidity recovery efficiency 77% Supply air: 30 m3/ h Supply by zone;	Sensible heat recovery efficiency: 85% Latent heat recovery efficiency: 85% Minimum fresh air Supply by zone
Airtightness	0.6ach	0.6ach
Heating	Heat recovered form MVHR system Air source heat pump	Heat recovered form MVHR system Air conditioning with Cop of 1.2 Schedule set by room activity
Cooling	Air cooling with recirculation supply Additional dehumidification with seasonal energy efficiency ratio 3.2	Air conditioning with CoP of 1.8 Schedule set by room activity
Window shading	Additional reduction factor summer shading: 10% for all outside windows	Blinds shading with low solar reflectance placed on outside of the window, operated during May to Sep with a modified schedule
Natural ventilation	Additional ventilation when outdoor climate was suitable and turned off if indoor temperature lower than 20 °C	Natural ventilation turned on when outdoor temperature was between 20 to 25 °C

The building system settings in the PHPP simulation are summarised in Table 4-5, which also shows the difference with the settings in DesignBuilder. The differences occurred mostly because of the different characteristics of the two software and how their operating modes were completely different. For the MVHR system, the most similar system was selected from the PHPP menu, and while it had a slightly lower latent heat recovery efficiency, the airtightness level was the same in both programs. For the heating and cooling, PHPP did not require a schedule to control the system operation, which is different from DesignBuilder. The shading method is different between the two programs as well. DesignBuilder uses window blinds shading, which is controlled by a schedule, while in PHPP a shading reduction factor only for summertime can be added, a 10% factor is applied, which could prevent 90% of solar heat from passing through the glazing. Finally, the two programs' settings for natural ventilation were similar and controlled by the outdoor temperature.

4.9.2. PHPP results

Running the PHPP simulation of the case building with the retrofitting measures, illustrated in Table 4-4 and Table 4-5, confirmed that the EnerPHit standard had been met. The results of the case building after retrofit on the PHPP verification worksheet are presented in Figure 4-18, where the energy demand for heating and cooling were 13 kWh/m^{2}a and 25 kWh/m^{2}a, respectively, and the primary energy demand was 108 kWh/m^{2}a, which was the total energy consumption of the building including heating, cooling, lighting and unregulated energy. The criteria for cooling demand, 27 kWh/m^{2}a, in PHPP was adjusted based on weather condition and included dehumidification demand. Thus it is different from the value (15 kWh/m^{2}a) in the PHI EnerPHit standard.



Specific building characteristics with reference to the treated floor area

					Criteria	Alternative criteria	Fulfilled?[2]
	Treated floor area	m²	252.0				
Space heating	Heating demand	kWh/(m²a)	13	≤	20	-	yes
	Heating load	W/m²	10	≤	-	-	
Space cooling	Cooling & dehum. demand	kWh/(m²a)	25	≤	27	33	yes
	Cooling load	W/m²	7	≤	-	11	
	Frequency of overheating (> 25 °C)	%	-	≤	-		-
	Frequency of excessively high humidity (> 12 g/kg)	%	0	≤	10		yes
Airtightness	Pressurization test result n_{50}	1/h	0.6	≤	1.0		yes
Non-renewable Primary Energy (PE)	PE demand	kWh/(m²a)	108	≤	120		yes
Primary Energy Renewable (PER)	PER demand	kWh/(m²a)	83	≤	-	-	-
	Generation of renewable energy (in relation to projected building footprint area)	kWh/(m²a)	0	≥	-	-	

[2] Empty field: Data missing; '-': No requirement

I confirm that the values given herein have been determined following the PHPP methodology and based on the characteristic values of the building. The PHPP calculations are attached to this verification.

EnerPHit Classic? yes

Task: First name: Surname: Signature:

Issued on: City:

Figure 4-18: Energy demands of the retrofitted case building calculated by PHPP.

The PHPP simulated energy consumption of the case building was compared with that simulated by DesignBuilder, and the results are shown in Figure 4-19. It is necessary to keep in mind that the ways that the DesignBuilder and PHPP software calculate the energy demand are very different. The former is a dynamic simulation that factors in the occupancy activities, weather change and operating from schedule control, while the latter is a static calculation where all the factors are based on a set value. Under this condition, the PHPP value (13 kWh/m^{2}a) and DesignBuilder value (14.9 kWh/m^{2}a) for heating demand were considered not very different, and are 35% and 25% lower, respectively, than the criteria of 20 kWh/m^{2}a. As the heating demands were close, this can be explained because the inputs of factors such as envelope insulation and MVHR system, which significantly affected the heating demand, were similar in both software. For the cooling demand, the PHPP simulated result (25 kWh/m^{2}a) was much higher than the DesignBuilder result of 11.5 kWh/m^{2}a, which is mainly explained because the energy used by the additional dehumidifier was included, which consumed 7.5 kWh/m^{2}a energy by PHPP calculation.

Because this research mainly focused on reducing heating and cooling energy demand brought by retrofitting measures, only those two energy demands were compared in detail against the EnerPHit standard. However, to improve the integrity of this Passivhaus standard retrofitting, the total primary energy consumption of the retrofitted case was calculated by DesignBuilder and PHPP and illustrated in Figure 4-19. The primary energy demand was calculated directly by PHPP, since it is an important indicator for Passivhaus, while DesignBuilder only simulates the energy demand based on secondary energy that can be used directly. In order to maintain consistency, the primary energy (PE) factors used by PHPP were adopted for the DesignBuilder primary energy results. Electricity was the sole energy supply selected in DesignBuilder, for which the PE factor is 2.6, according to PHPP. However, PHPP considered the same except in that the domestic hot water (DHW) was supplied by natural gas for which the PE factor is 1.1. In order to make a fair comparison, the DesignBuilder simulated energy demand for DWH was converted with the natural gas PE factor. As with the results shown in Figure 4-19, the primary energy demand figures based on PHPP and DesignBuilder were 108 kWh/m^{2}a and 146.5 kWh/m^{2}a, respectively, so the former met with the EnerPHit requirement of 120 kWh/m^{2}a, but the latter exceeded this requirement. The reason for this significant difference was mainly because the energy consumption for room electricity, lighting and DWH was much higher in DesignBuilder than in PHPP. The PHPP simulation only considered factors with the lowest amount of usage based on its guidance and the yearly energy consumptions were calculated based on the software's default frequency of use that cannot be modified. On the other hand, DesignBuilder simulated those usages with a standard domestic schedule, and only the lighting was changed to LED lighting, which was more energy efficient, and others remained unchanged. Thus, to achieve the full energy requirement of the EnerPHit standard, not only should heating/cooling energy efficiency be significantly improved, but also the energy efficiency of all other household applications, and observing a prudent energy usage lifestyle.

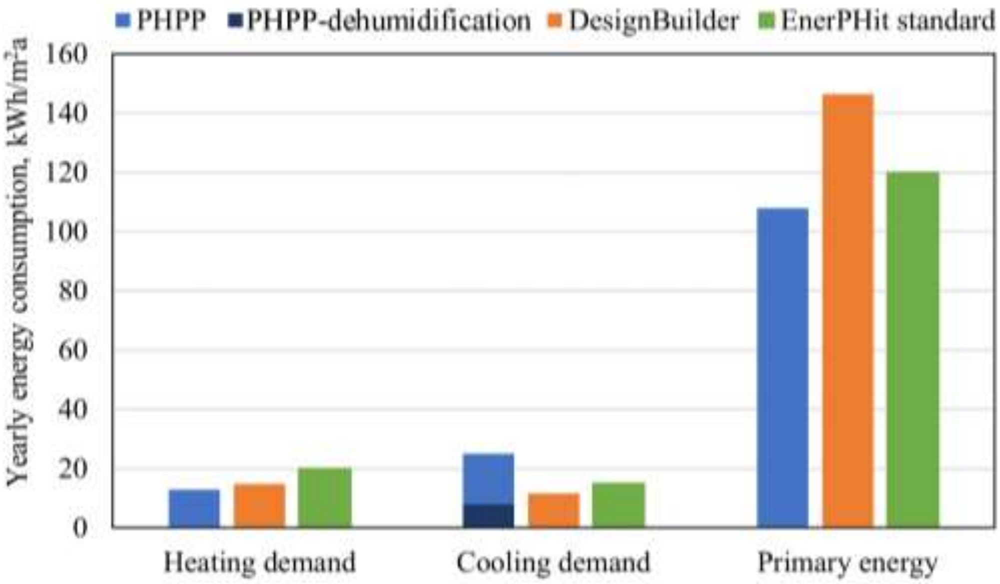


Figure 4-19: Comparing the PHPP and DesignBuilder simulated energy demands with the EnerPHit standard

In general, the inputs of PHPP were kept as consistent as possible with DesignBuilder's inputs. However, because of the different characteristics of the two software, there were differences between the two simulated results regarding the energy performance of the virtually retrofitted case building as mentioned above. Nevertheless, the results of both software packages achieved the requirements of the EnerPHit standard, which shows the effectiveness of the applied retrofitting measures. Since DesignBuilder operates with dynamic simulations with the much more detailed hourly weather data to support the building performance calculation, rather than the monthly weather data utilised by PHPP, this study tended towards DesignBuilder results and adopted them to continue the subsequent research.

4.10. Summary

This chapter has considered the application of the Passivhaus EnerPHit retrofitting standard to the studied building to evaluate the effectiveness of the standard under the hot summer – cold winter climate. The step-by-step retrofitting measures, from insulating the exterior envelope to applying a high-performance mechanical ventilation system, were simulated to determine the suitable solutions for this case. Although there was a difference in the results simulated by DesignBuilder and PHPP for the discussed reasons, it was concluded that it was possible to retrofit this building to the EnerPHit standard, giving significantly reduced energy demand for both heating and cooling.

From the DesignBuilder simulated results, heating was the dominant energy demand of the pre-retrofitted building due to the heat losses through the uninsulated, leaky envelope. The heating demand was susceptible to the opaque envelope insulating measures (40% energy saved) and airtightness level (40% energy saved), and, together with the energy saved from high-performance windows (8%), the energy consumption was down to the required EnerPHit standard value. For cooling demand, the contribution from the high thermal insulation opaque envelope (12%) was smaller than from the low airtightness (16%) and high-performance windows (18%). A MVHR system was essential to supply fresh air to the indoor space under the studied climate because the outdoor thermal environment could not provide indoor comfort with natural ventilation for most of the year. This case study adopted an MVHR system with 85% sensible heat recovery efficiency and 80% latent heat recovery. The latent heat recovery function is fundamental for this climate because of the high humidity, and this function helps reduce the cooling demand by about 5 kWh/m^{2}a. As a result of the retrofit measure, the heating demand achieved the EnerPHit standard, but the cooling demand did not meet the standard until passive cooling measures were adopted. Using blinds with low solar reflectance (0.2) outside the window was the most efficient shading way to reduce the cooling demand while using natural ventilation when the outdoor temperature was under the Passivhaus comfort range of 20°C to 25°C slightly reduced the cooling demand.

With all the retrofitting measures, the final achieved heating (14.9 kWh/m^{2}a) and cooling (11.5 kWh/m^{2}a) demands were about 25% and 23% below the EnerPHit criteria, which suggested that the applied retrofitting plan was not the optimal solution when considering the retrofitting intensity, and that some reduction in the applied measures could be made whilst still meeting the standard. This motivated the research in the next chapter about updating the retrofitting strategy for the studied dwelling.

Chapter 5. Improving the retrofitting plan and evaluating the retrofitted thermal comfort

5.1. Overview

The retrofitted case in Chapter 4 showed an energy-saving efficiency that surpassed the EnerPHit standard's requirement by 25% in heating and 23% in cooling due to over-sizing of retrofitting inputs. These results suggested that retrofitting measures could be applied more efficiently, thus achieving a better balance between the EnerPHit goal and the environmental impacts from the retrofitting materials. For Passivhaus, mechanical components such as ventilation, heating or cooling systems, are necessary depending on the climate type, and the size of the system would not change unless the demand changed significantly (Schnieders et al., 2015). Those systems are all necessary for regions with hot summer - cold winter climates, and retrofitting in such regions is more likely to focus on the fabric of the building envelope. Thus, this chapter explores the possibility of upgrading the case building’s envelope so that EnerPHit criteria could be met whilst reducing the overall retrofit environmental impact.

5.2. Method for improving the retrofitting plan

The main research objective of this chapter was to investigate the retrofitting solution for the case building, which aimed to achieve the EnerPHit standard energy performance with the lowest level of envelope insulation requirement. The overall method is demonstrated in Figure 5-1.

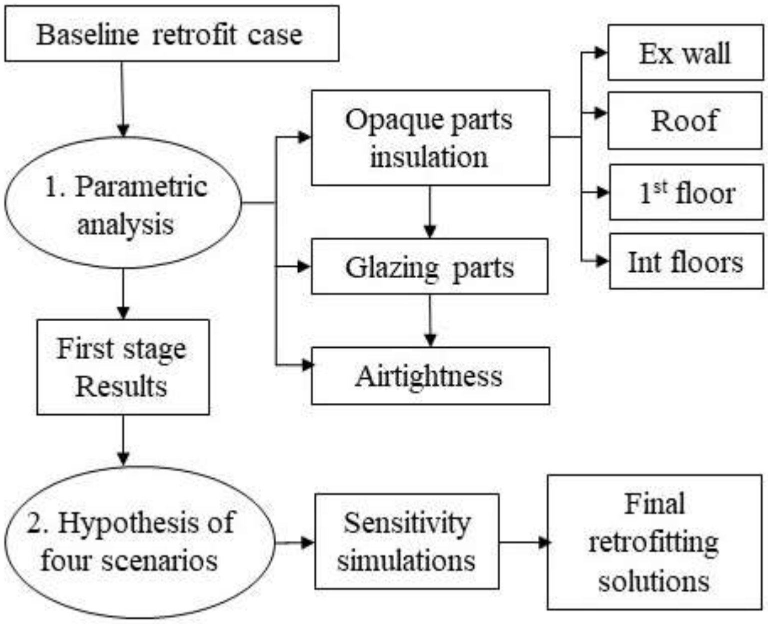


Figure 5-1: Process of improving the retrofitting plan

In the first stage, a series of parametric analyses were undertaken to evaluate the sensitivity of the insulation performance of each envelope component towards the building's energy consumption. The evaluated parameters included the exterior wall, roof, 1st floor, interior floors, and windows. Envelope airtightness level was also investigated due to its significant effect on energy consumption. For the opaque components, the insulation performance was examined according to various thicknesses of insulation layers, from a relatively thin layer of 50mm, to the baseline retrofit model adopted thickness of 250mm, and with a simulation step of 25mm, which is the thinnest thickness of Rockwool insulation board that most local suppliers provide. Materials other than Rockwool were not considered in the parametric analysis because the primary intent was to evaluate the relationship between the envelope thermal transmittance and building energy consumption, and different insulation materials could achieve the same thermal performance with different usage amounts.

The thermal performance of the windows was assessed with two points of focus – the U-value and the solar heat gain coefficient (SHGC). For the airtightness level, the studied range was from the EnerPHit standard maximum allowed value of 1.0 ach to the value adopted in the baseline retrofit model, 0.6 ach. Airtightness levels better than 0.6 ach were not examined, given the restrictions of the existing structure. As a result, the analysis results should provide evidence about the parameters that could heavily influence energy consumption worth retaining for high thermal performance. Conversely, those parameters which did not strongly influence thermal performance could be reduced.

In the second stage, four scenarios of retrofitting measures were hypothesized, and retrofitting plans were analysed for these four scenarios. Combinations of different retrofitting measures were examined through sensitivity simulations, and the combinations most suited to achieve the EnerPHit standard with the lowest level of insulation material inputs were considered as the final retrofitting solution. The combinations for simulation were based on the parametric analysis results in which the impact of envelope components on building energy consumption were indicated. Then, the sensitivity simulations were progressed in a way that small changes in insulation thickness were made based on energy demand results of the previous tested combinations until the combination most close the research purpose was found under each scenario. The final combinations found under the four scenarios were considered as improved retrofitting solutions because different amounts of insulation inputs could be saved compared with the baseline retrofit case.

5.3. Parametric analysis

In this section, a series of parametric analyses were carried out for each of the opaque and transparent envelope components and for the airtightness to explore how these affected the building's energy consumption. Therefore, the possibility of reducing the thermal requirement of each of the envelope components without significantly impairing the energy performance could be examined for the final aim of improving the retrofitting plan.

5.3.1. Opaque envelope parameters

Energy-efficient buildings can maintain a comfortable indoor environment with a low energy consumption during the operational stage because of the extra amount of insulation materials and energy-efficiency products applied to the building at the construction stage. Yet, those extra materials consumed a significant amount of energy in the manufacturing process (Thormark, 2002; Ibnmohammed *et al.*, 2013). For example, a study stated that a building built to Passivhaus standard in China consumed 42% more energy in the construction stage than if it was built to the local building regulation (Su et al., 2020).

For the case building of this research that aimed to achieve the EnerPHit standard, it is meaningful to minimise the required insulation material and decrease the material manufacturing stage energy consumption, under the premise that the target energy saving is achieved at the building operation stage. In addition, less usage of the insulation material contributes to reducing carbon emissions and improving cost efficiency (Raimundo, Saraiva, & Oliveira, 2020). Therefore, parametric analysis about opaque envelope components was carried out in this section to explore how their thermal performance influences the building energy consumption.

The analysed envelope parameters included the exterior wall, floors and roof. Because the ground floor of the case building was for commercial usage and excluded from the retrofitting, the floor slab of the first floor was actually the enclosure of the residential space considered for retrofitting. For clarity, the first floor was expressed as '1st floor', and 'interior floor' was used to denote the second and third floor of the building. As mentioned earlier, the DesignBuilder simulations of the parametric analysis were based on the previously retrofitted case, in which the insulation material was 250mm thick Rockwool for the whole envelope. Other insulation materials were not considered in the parametric analysis because the primary purpose was to evaluate the relationship between the envelope thermal transmittance and building energy consumption, and different insulation materials could achieve the same thermal performance with different usage amounts. Thus, the thermal performance was evaluated by changing the thickness of Rockwool which was applied to the envelope components.

Table 5-1 illustrates the U-value of each of the opaque envelope components when the different thickness of insulation material was virtually applied through DesignBuilder simulation. The Passivhaus standard suggested that the U-value of opaque envelope components should not fall below 0.3 W/m^2k for retrofitting buildings in order to achieve the energy goal. From Table 5-1, it could be seen that the U-value of each component improved significantly from the examined lowest insulation thickness of 50mm to the thickest of 250mm, while when the insulation thickness was lower than 100mm, the U-value of all the components failed to achieve the standard suggested thermal performance.

Table 5-1: Opaque components' U-value (W/m²K) when different thicknesses of insulation material are applied

	50 mm	75 mm	100 mm	125 mm	150 mm	175 mm	200 mm	225 mm	250 mm
	U- values (W/m²K)								
Ex wall	0.516	0.317	0.29	0.238	0.201	0.175	0.154	0.138	0.125
Roof	0.495	0.36	0.283	0.233	0.198	0.172	0.152	0.137	0.124
1st floor	0.530	0.378	0.294	0.240	0.203	0.176	0.155	0.139	0.126
Int floor	0.530	0.378	0.294	0.240	0.203	0.176	0.155	0.139	0.126

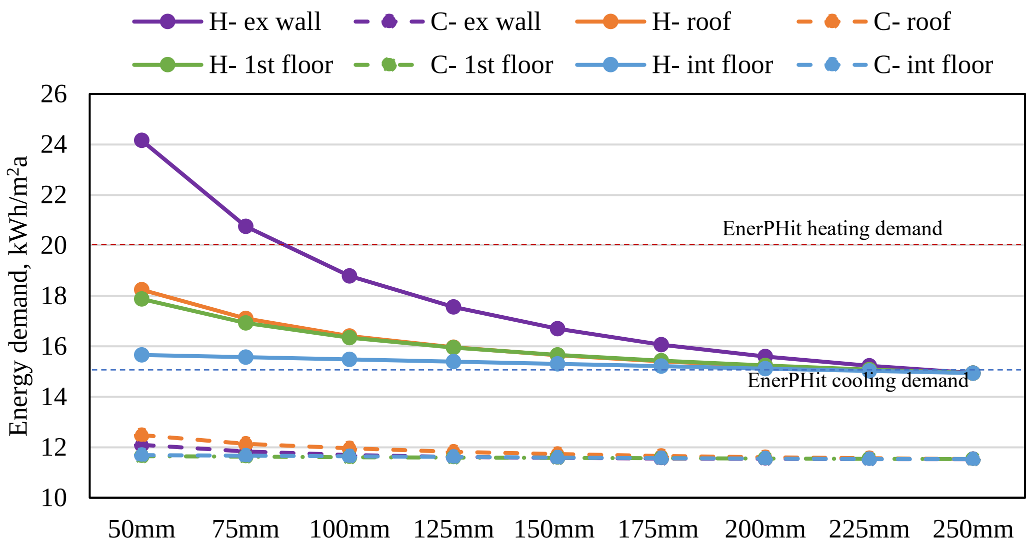


Figure 5-2: Parametric analysis for each opaque envelope component's insulation thickness impacts on the building's heating demand (H) and cooling demand (C).

Figure 5-2 indicates the parametric analysis results of how the thermal performance of different opaque envelope components influenced the energy demand of the case building. Those simulations were done in a way where the insulation thickness of one parameter changes and the others remained unchanged at the baseline retrofit condition. In general, the results show that the insulation thickness had a much greater effect on heating energy demand than on cooling energy demand. For the envelope components performance with regard to the heating demand, the effect for the exterior wall was the most significant, as the demand decreased from 24.2 kWh/m²a, when the insulation was 50mm thick, to 14.9 kWh/m²a, when the insulation thickness was the adopted value of 250mm from the previous retrofitting process (a 38% reduction). However, the heating energy demand exceeded the EnerPHit criteria of 20 kWh/m^2a when the exterior wall insulation thickness was below 100mm. The thermal performance of the roof had a secondary effect on heating, with the demand dropping for both by about 3.3 kWh/m^2a (18%) when the insulation thickness increased from 50mm to 250mm. A slightly lower effectiveness was found in the 1st floor slab; the corresponding heating demand changed by 3 kWh/m^2a (17%) from the simulated thinnest to thickest insulation. Furthermore, it can be seen that the interior floors slabs had the least effect as the decrease in energy demand was only 0.8 kWh/m^2a, with 5% effectiveness in heating demand in the tested thickness range. However, the roof is the most effective envelope part for the cooling demand, which showed a 1 kWh/m^2a decline in demand after the insulation thickness increased from 50mm to 250mm. For the exterior wall, the reduction was only 0.6 kWh/m^2a in the tested thickness range. Moreover, as can be seen in Figure 5-2, the thermal performance improvement of the 1st floor and interior floor slabs did not affect the cooling demand. Therefore, the parametric analysis suggested that the overall effect on cooling energy saving of increasing the insulation thickness was relatively weak, even each of the components had a different effect on it. However, the parametric analysis was based on the retrofitted baseline case, in which case when one parameter changes, the others maintained the previous proposed retrofitting measures. In order to know whether the insulation material helped in reducing the cooling energy consumption, the energy demand was simulated when the opaque components had no insulation applied, while other retrofitting measures were kept the same with the retrofitted baseline case. Figure 5-3 shows the simulated cooling demand was 20.3kWh/m^2a under this condition, which was higher than the retrofitted baseline case to a certain degree. Combined with the parametric analysis results, it could be seen that insulating the opaque components was helpful to reduce the cooling energy, while this could be achieved without necessarily thick insulation.

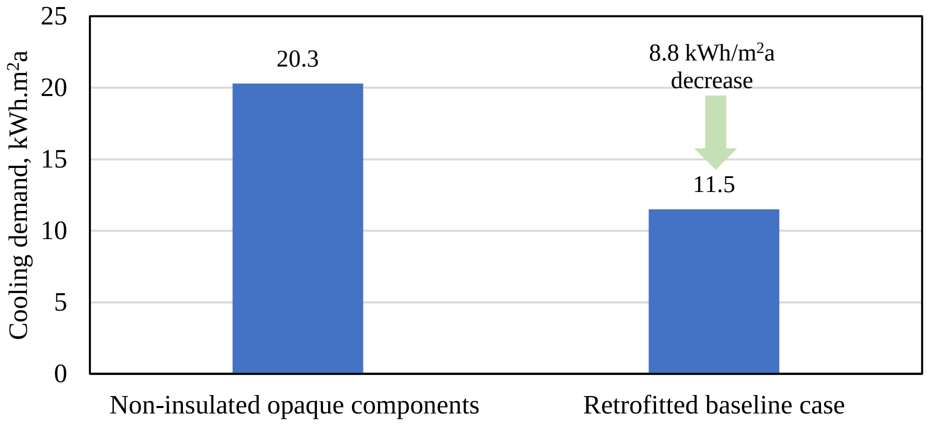


Figure 5-3：Cooling demand comparison between the case in which the opaque components had no insulation and the retrofitted baseline case

In conclusion, these findings suggest that the heating demand is the leading factor for deciding the thermal performance of the opaque envelope components as the high thermal performance envelope had a limited effect in decreasing the cooling demand, and the required insulation thickness for achieving the heating energy criteria is largely able to achieve the cooling criteria in the same time. Regarding the effectiveness of the impact of opaque components on the heating demand, the exterior wall ranked the highest, then the roof and first floor, which had a similar influence, and the interior floors had a minor influence. Thus, a high insulation thickness value should be kept for the exterior wall, and a reasonable insulation thickness should be used for the roof and 1^{st} floor slab. However, for the interior floor slabs, the insulation material could be entirely removed, as it had such a negligible effect on both heating and cooling demand.

5.3.2. Glazing type

The transparent part of the envelope has been considered as the weak part of the envelope because it is responsible for a relatively large percentage of heat loss when comparing its area with the area of other opaque envelope components. Taking the pre-retrofit case building as an example, the total envelope heat loss was examined in section 4.3, and the glazing part was responsible for 25%, while it only accounts for around 8% of the entire envelope area. Thus, a window with a low thermal transmittance is usually required for energy efficient buildings. Regarding glazing performance, excepting the thermal transmittance which was assessed by U-value, the solar heat gain coefficient (SHGC) is another main factor which has a close relationship with the indoor heat gain/loss and the building energy consumption (Feist et al., 2005; Gasparella, Pernigotto, Cappelletti, Romagnoni, & Baggio, 2011).

In the retrofitted baseline case, a Passivhaus certificated triple glazed window type was simulated as the replacement of the single glazed window in the pre-retrofit case. However, some research suggested that it could meet the Passivhaus standard by applying double glazing windows with a higher U-value in hot climates (Onio Figueiredo, Figueira, Vicente, & Maio, 2016) Sigalingging, 2019). To verify this for the studied climate, ten types of glazing were tested, which were mostly triple glazed, except for one double glazed window with a relatively high U-value of 2.55 W/m^2K. Glazing with a higher U-value than this was not considered in the parametric analysis because the corresponding heating demand would exceed the EnerPHit standard required. The difference in yearly heating and cooling energy demand was simulated when each individual glazing type was adopted by the case building. The best performance shading method examined in the previous chapter was modelled for all the glazing types to avoid differences in energy consumption caused by shading methods. The results are shown in Figure 5-4.

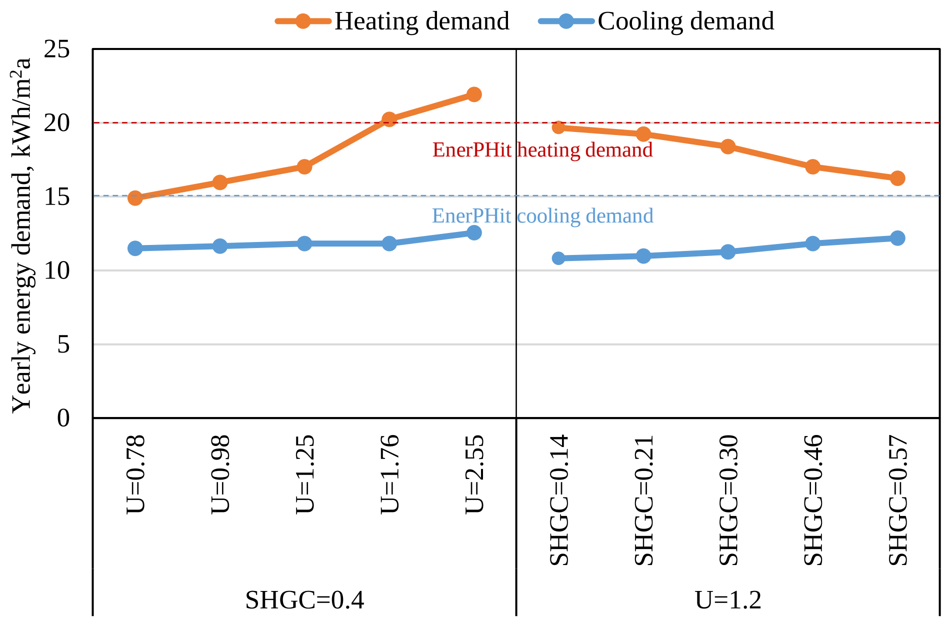


Figure 5-4: Parametric analysis of the impact of glazing type on the building's heating demand (H) and cooling demand (C)

The ten types of tested glazing were divided into two groups of five, where the first group had the same fixed moderate SHGC value of 0.4 while the U-values were increased from a high performance of 0.78 W/m^{2}K to a relative poor performance of 2.55 W/m^{2}K - see Figure 5-4 (left). When using these five glazing types, the corresponding heating demand ranged from 14.9 kWh/m^{2}a to highest of 21.9 kWh/m^{2}a. The heating demand rose gradually with increasing U-value until the U-value exceeded 1.25 W/m^{2}K, (a moderate performance triple glazed window), when the heating demand increased at a much greater rate. The corresponding cooling demand has a narrower range, from 11.5 kWh/m^{2}a to 12.5 kWh/m^{2}a, with the increase in U-value having a very small impact on cooling demand until the glazing U-value rose to 2.55 W/m^{2}K (a double glazed window). For the second group, shown on the right-hand side of Figure 5-4, the five glazing types had the same moderate U-value of 1.2 W/m^{2}K, but the SHGC values were increased from 0.14 to 0.57. The results show that the heating demand fell from 19.7 kWh/m^{2}a to 16.2 kWh/m^{2}a following the SHGC increases, while the cooling demand was increased from 10.8 kWh/m^{2}a to 12.2

kWh/m^2a. Thus, the increase in SHGC is beneficial to the heating energy demand, but worsens the cooling energy demand.

Therefore, the parametric analysis results suggested that the U-value of the glazing had a strong positive influence on the heating demand but a negligible effect on the cooling demand. The SHGC performance had a negative effect on heating demand, but a positive respect on cooling demand. Among the examined ten glazing types, those with a U-value of 0.78 W/m^2K and a SHGC value of 0.4 had the best performance for both heating and cooling. All the tested glazing types were within the EnerPHit energy criteria, except for the double glazing type, which failed to meet the requirement for heating. This suggests that high thermal performance glazing is necessary for the hot summer - cold winter climate area. Moreover, the glazing types with a moderate SHGC value were more suitable for the case building under the studied climate, which did not cause extreme heating or cooling energy consumption.

5.3.3. Airtightness

Airtightness performance has been a significant parameter for building envelope because it strongly relates with the building energy efficiency and indoor air quality. Both heating and cooling energy consumption increase in the presence of a poor airtightness situation, because interstitial condensation problems within the envelope components and increased envelope thermal transmittance are most likely to happen (Tanyer, Tavukcuoglu, & Bekboliev, 2018). However, the influence of airtightness performance on heating and cooling demand could be quite distinctive for different types of building under different climate conditions. In regard to the principles of Passivhaus, a good airtightness performance is required to achieve the decrease of the indoor heat loss through envelope infiltration and the airtight envelope also to improve the actual operational efficiency of the MVHR system.

The retrofitting results in Chapter 4 suggested that the improvement of airtightness performance was a significantmeasure for decreasing both heating and cooling energy demand of the case building, but the sensitivity of improving the airtightness performance to heating and cooling demand was unknown. Thus, a parametric analysis about airtightness is performed in this section. The tested range of airtightness level for the case building was from the EnerPHit standard required maximum value of 1.0ach to the previous retrofitting adopted value of 0.6ach. Airtightness levels lower than 0.6ach was not considered because it should be challenging to achieve in practice, as discussed in section 4.4. Moreover, the parametric airtightness analysis was studied with the simulation step of 0.1ach, and the result is shown in Figure 5-5.

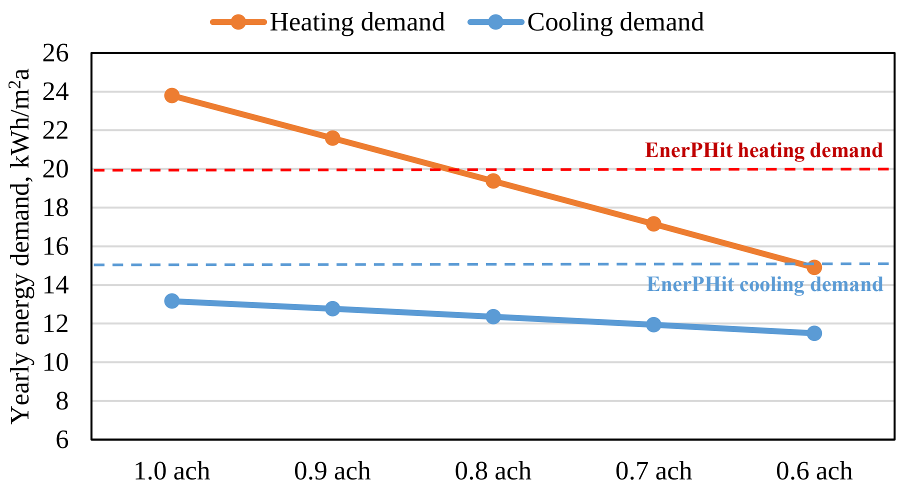


Figure 5-5: Parametric analysis for airtightness towards the building's heating demand (H) and cooling demand (C)

Figure 5-5 indicates that lowering the envelope's air leakage (i.e., lowering the air changes per hour) led to a decreasing energy trend in heating and cooling, but with different efficiencies. The heating consumption dropped gradually from 23.8 kWh/m^{2}a to 14.9 kWh/m^{2}a following the airtightness change from 1.0ach to 0.6ach, a 37% energy saving. Moreover, it is worth noting that when the case building was simulated with an airtightness level of 0.9ach, the heating demand was 21.6 kWh/m^{2}a, which exceeds the EnerPHit standard requirement, and therefore 0.8ach was the maximum acceptable airtightness level for meeting the heating demand criteria.

On the other hand, the airtightness level had a lesser effect on the cooling, as the demand changed from 13.2 kWh/m^{2}a to 11.5 kWh/m^{2}a, with a 13% energy saving over the tested range. The cooling demand was below the EnerPHit criteria even with the tested worst airtightness level of 1.0ach. However, taking both heating and cooling demand into consideration, only the airtightness range between 0.8ach and 0.6ach was desirable to achieve the overall EnerPHit standard.

5.4. Retrofitting Scenarios

5.4.1. Hypotheses of four scenarios

The four scenarios are summarised in Table 5-2, and each had limitations on certain retrofit measures.

Table 5-2: The four considered scenarios for envelope performance upgrading.

	Assumed settings for each scenario
Scenario 1	The best achievable airtightness level is assumed as 0.8ach because this level was the lowest acceptable level for achieving the energy criteria based on parametric analysis.
Scenario 2	The retrofitting intensity for all the envelope elements is assumed to be reduced simultaneously, as this allows the reduction in insulation material of different envelope components to be reasonably decided based on how they affect the building energy demand.
Scenario 3	The best achievable airtightness level is assumed as 0.6ach because this level was considered as the best achievable in retrofits in this research.
Scenario 4	The best achievable airtightness level is assumed as 0.6ach. Also, windows are assumed to have a U-value of 0.78 W/m²K, which is the best in the local market. This assumption was made because it was curious to see what is the required opaque insulation level to achieve the criteria when other parameters are at the optimum levels as tested in this research.

In addition, the hypothesis of the four scenarios was made partly according to the parametric analysis results, such as in scenario 1, where the airtightness level of 0.8 ach was assumed to be the best achievable level because the parametric analysis result showed that the case building is not able to meet the targeted criteria with a level worse than 0.8ach. For scenario 2, a situation was assumed that the retrofitting for all envelope parameters was reduced simultaneously from the baseline retrofit model. Similarly, an airtightness level of 0.6ach was assumed to be realised under scenario 3 since it is the best performance considered in this study. In scenario 4, a high performance of glazing with a U-value of 0.78 W/m²K was assumed, based on scenario 3. According to the researchers' field investigation, this glazing value is very close with the most widely used product (U-value around 0.8 W/m^2K) in Passivhaus buildings in China. It is reasonable to suggest those scenarios for analysing the retrofitting plans, but this part of study only considered the retrofitting solution depending on the single factor of energy consumption. The retrofitting plans were then analysed through sensitivity simulation under the consideration of the limitations in each assumed scenario.

5.4.2. *Sensitivity simulation*

Under the four scenarios, combinations of envelope parameters with suitable thermal properties were tested through sensitive simulation to identify those that could achieve the EnerPHit energy standard with the minimum level of insulation material input. Due to insulating the interior floors barely helping with energy saving, it was decided not to apply insulation material to the interior floors under all scenarios. Thus, only the other five envelope parameters (exterior wall, roof, 1st floor, glazing and airtightness) were considered as part of the combinations for sensitivity simulations.

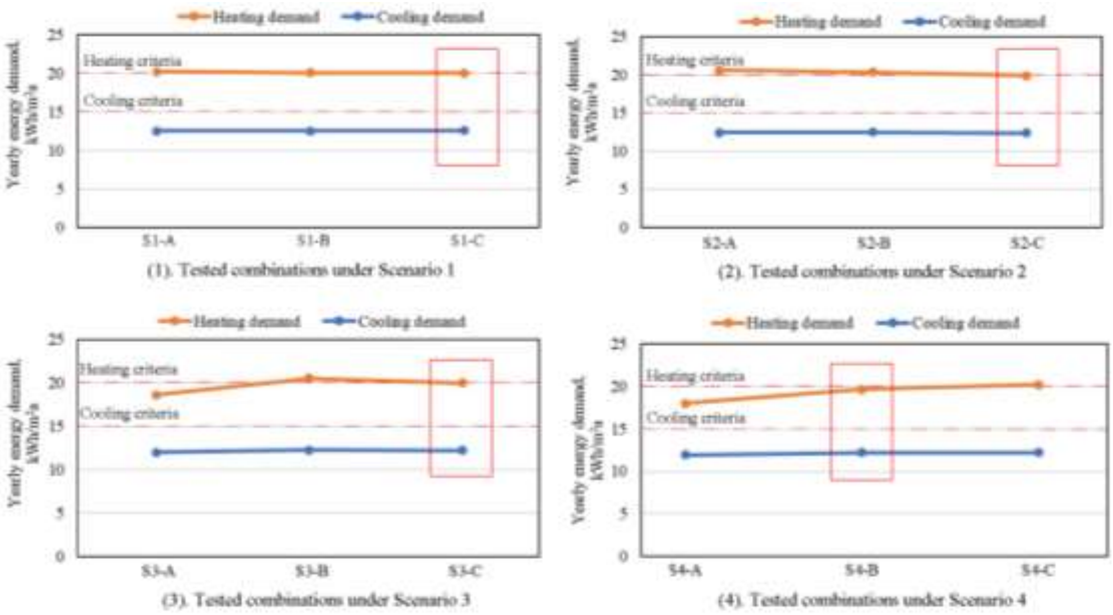


Figure 5-6: Simulated energy demands of the retrofitting combinations under the four scenarios, with the best combination marked in red rectangle.

Table 5-3: The energy demand and insulation thickness of the tested combinations under the four scenarios.

Tested combinations under Scenario 1			
Combinations	S1-A	S1-B	S1-C
Energy demand	H*:20.2 C*:12.5	H:20.1 C:12.5	H:20.0 C:12.6
Ex wall	275mm	275mm	300mm
Roof	250mm	275mm	250mm
Floor	250mm	250mm	250mm
Glazing	U*:0.78	U:0.78	U:0.78

Tested combinations under Scenario 2			
Combinations	S2-A	S2-B	S2-C
Energy demand	H:20.6 C:12.4	H:20.3 C:12.4	H:19.9 C:12.4
Ex wall	225mm	250mm	250mm
Roof	175mm	175mm	200mm
Floor	150mm	150mm	175mm
Glazing	U:0.98	U:0.98	U:0.98

Tested combinations under Scenario 3			
Combinations	S3-A	S3-B	S3-C
Energy demand	H:18.6 C:12.0	H:20.5 C:12.3	H:19.9 C:12.2
Ex wall	200mm	200mm	225mm
Roof	175mm	150mm	175mm
Floor	150mm	100mm	100mm
glazing	U:0.98	U:1.25	U:1.25

Tested combinations under Scenario 4			
Combinations	S4-A	S4-B	S4-C
Energy demand	H:18.0 C:11.9	H:19.7 C:12.2	H:20.2 C:12.2
Ex wall	175mm	175mm	175mm
Roof	150mm	100mm	100mm
Floor	175mm	100mm	75mm

*H: heating energy demand (kWh/m^2a); C: cooling energy demand (kWh/m^2a); U: U-value (W/m^2k).

Figure 5-6 demonstrates the sensitivity simulation results under the four scenarios, where the energy consumption of the tested combinations are shown and the best combinations that achieve the EnerPHit energy criteria with the lowest level of insulation requirement are marked with red rectangles. Table 5-3 illustrates the specific energy demands on heating and cooling of each combination and the envelope parameters' details. However, some parameters were assumed at particular values in the four scenarios, so this table only shows the remaining parameters. From the combined view of the figure and table, it can be seen that small changes in thermal performance of the envelope components resulted in difference in building energy consumption For the best combinations under the four scenarios, the point in common was that the insulation material was the thickest for the exterior walls, and the insulation thickness for other opaque components could be much less because the exterior wall is the parameter with the strongest connection to a building's energy demand in the studied climate. Those four best combinations were considered as the improved retrofitting plans from the baseline retrofit case because they have achieved the target which was set earlier in this chapter.

5.4.3. Difference between the retrofitting plans

For the four improved retrofitting plans, namely ‘improved 1’ for the improved plan under scenario 1 and so on, their heating and cooling energy demands were all around 20 kWh/m^{2}a and 12 kWh/m^{2}a, respectively. However, the overall thermal properties of the improved plans were quite different for achieving the same energy performance. Table 5-4 lists the detail of the insulation thickness of each envelope component in the improved retrofitting plans and that of the baseline case for comparison. The U-values could be seen in conjunction with Table 5-1, and it should be remembered that each of the scenarios had different assumptions for which the details are shown in Table 5-2.

Table 5-4: Comparison of the required insulation thickness and performance of glazing and airtightness between the baseline retrofit case and the retrofit plans improved under the four scenarios.

Cases	Wall insulation (mm)	Roof insulation (mm)	1st floor insulation (mm)	Glazing U-value (W/m^2K)	Airtightness level (ach)
Baseline	250	250	250	0.78	0.6
Improved 1	300	250	250	0.78	0.8
Improved 2	250	175	150	0.98	0.7
Improved 3	225	175	100	1.25	0.6
Improved 4	175	100	100	0.78	0.6

Among the four scenarios, it was found that the influence of the airtightness level upon the required envelope thermal performance to meet the standard was quite distinct. By comparing the plans under scenarios 1 and 4, the applied glazing was the same while the airtightness performance was 0.8ach and 0.6ach in scenarios 1 and 4 relatively. This resulted in a dramatic difference to the opaque insulation thickness, in which the thicknesses for exterior wall, roof and 1st floor were 300mm, 250mm and 250mm under scenario 1, while in scenario 4, the level for the same components changed to 175mm, 100mm and 100mm. For scenario 2, although the airtightness level and glazing performance were worse than that in the baseline retrofit case, the retrofitting solution with a lower insulation level in roof (175mm) and 1st floor (150mm) managed to reach the EnerPHit standard. Comparing scenarios 3 and 4, which had the same standard of airtightness performance, because the glazing performance was lower with a U-value of 1.25 W/m^2K in scenario 3, a higher level of insulation on the exterior wall (225mm) and roof (175mm) was required in this scenario.

An energy demand comparison between the pre-retrofit case, EnerPHit requirement, baseline retrofit plan, and the improved retrofit plans is illustrated in Figure 5-7. Overall, the energy saving efficiency from the four improved retrofit plans were considered high, around 87% of heating energy and 70% of cooling energy were saved from the pre-retrofit situation. Though this energy saving efficiency was slightly lower than the baseline retrofit plan could provide, the amounts of insulation mass required in the improved plans were lower. As shown in Figure 5-7, the baseline retrofit plan required a total insulation mass of 165m^3 for the entire envelope, while about 18%, 36%, 44% and 58% of the insulation mass could be saved in each of the improved plans. The insulation mass differences in each retrofitting plan should lead to a difference in their environmental impacts, and assessing this difference requires a detailed life cycle carbon analysis.

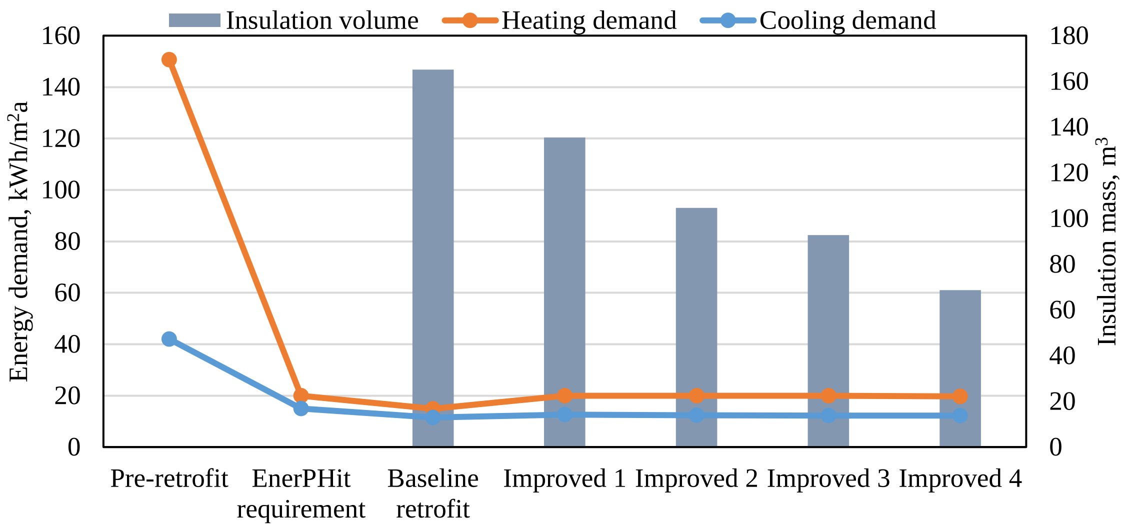


Figure 5-7: Comparing the energy demand between the pre-retrofit, baseline retrofit and improved retrofit plans against the EnerPHit stand-ard requirement.

5.5. Thermal comfort of the retrofitted case

Improving the indoor thermal comfort and energy efficiency of the case building were the main motivations of this retrofitting study to achieve the Passivhaus EnerPHit standard. The indoor thermal comfort of the existing case building was evaluated as unsatisfactory in section 3.5, based on the adaptive thermal comfort model method with the on-site recorded data. In this research stage, the case building was virtually retrofitted with the retrofitting plan improved under different scenarios, and the proposed retrofitting plans all successfully achieved the EnerPHit energy criteria. Therefore, the indoor thermal comfort of the retrofitted case building is investigated and compared with that in the pre-retrofit case in this section.

Thermal comfort is regarded as a subjective feeling towards the thermal environment, and the thermal comfort results are influenced by a combination of four environmental factors and two personal factors. The former includes air temperature, relative humidity, air velocity and radiant temperature, and the latter involves clothing insulation and metabolic heat (ISO 7730, 2005). The adaptive thermal comfort (ATC) model was used to evaluate the naturally ventilated pre-retrofit case, though it is not suitable for the retrofitted case which was mechanically conditioned. Instead, the predicted mean vote (PMV) model, which considered both environmental and personal factors, was adopted for assessment because the PMV model predicts the mean value of thermal votes in mechanically conditioned buildings for a large group of people under the same environmental condition, and this method is widely used in many national building regulations (Guillén-Lambea, Rodríguez-Soria, & Marín, 2017). According to ASHRAE 55, the PMV model predicts occupants' responses to thermal comfort based on a 7-points thermal sensation scale, which are demonstrated below in Table 5-5. A PMV of ±0.5 predicts 90% of a population satisfied. However, most buildings are rarely obtained with the maximum satisfaction around 80% (ASHRAE 55, 2017). DesignBuilder simulates all the up-mentioned six factors involved in PMV prediction and reports the PMV results. Thus DesignBuilder reported that PMV results were applied for the thermal comfort assessment of the retrofitted case building. The PMV results of the pre-retrofit under the condition of being actively heated/cooled were also simulated by DesignBuilder for a fair quantitative comparison with the retrofitted case.

Table 5-5: the 7-point scale of the PMV model

Thermal condition	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Votes	-3	-2	-1	0	+1	+2	+3

The indoor thermal comfort of the retrofitted case was also evaluated against Passivhaus standard comfort requirement. The Passivhaus standard only considered the factor of indoor temperature and required comfort temperature range of 20-25ºC, while temperatures above 25 ºC are considered as overheated. Moreover, for buildings without active cooling, the standard allows that for 10% of the hours in the year, the temperature is higher than 25ºC, while for actively cooled buildings, no overheated time is allowed (*Passivhaus Standard*, 2016). The overheating problem has been found in many Passivhaus buildings in recent years as increasingly more Passivhaus buildings were inhabited (Figueiredo, Kämpf, & Vicente, 2016; Mlakar & Štrancar, 2011b). Thus, the overheating problem of the retrofitted case building was also evaluated by the Passivhaus standard.

5.5.1. Retrofitted case indoor thermal condition

In this section, the indoor air temperature and relative humidity of the retrofitted case building are reviewed before evaluating thermal comfort. Because the case building has successfully achieved the EnerPHit energy criteria in Chapter 4 through a virtual retrofitting process, and then the retrofitting plan has been improved under four scenarios in previous sections in this chapter, thus there are five retrofitted cases. The monthly mean indoor temperature and relative humidity of the five retrofitted cases are demonstrated in Figure 5-8 and Figure 5-9, respectively. Because the five retrofitted cases were all mechanically conditioned and the MVHR system and heating/cooling system settings were the same, the simulated indoor temperature and relative humidity were very close, despite the thermal performance and airtightness performance which were different in each case. As shown in the figures below, the monthly mean indoor air temperature was changing from the lowest of 18.2ºC in January to the highest of 26.1ºC in July for all the five retrofitted cases, and the monthly mean relative humidity levels were changing within the range around 33% to 71%, with the lowest value in January and highest in June. Because the difference in the indoor thermal condition in each retrofitted case was minimum, and the requirement of insulation material of the improved retrofitting plan under scenario 4 was lowest, this case was selected for the following thermal comfort assessment.

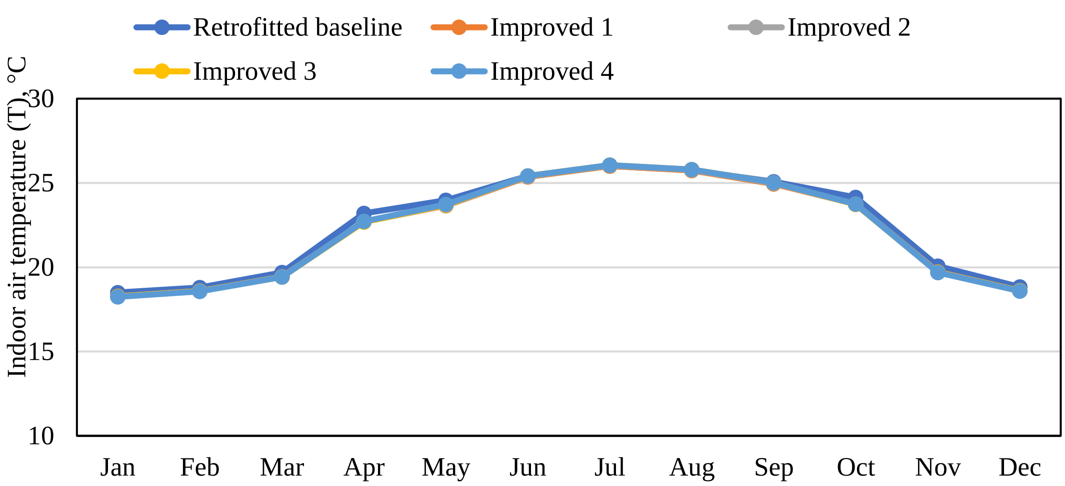


Figure 5-8: Comparison of monthly mean indoor air temperature between the five retrofitted cases.

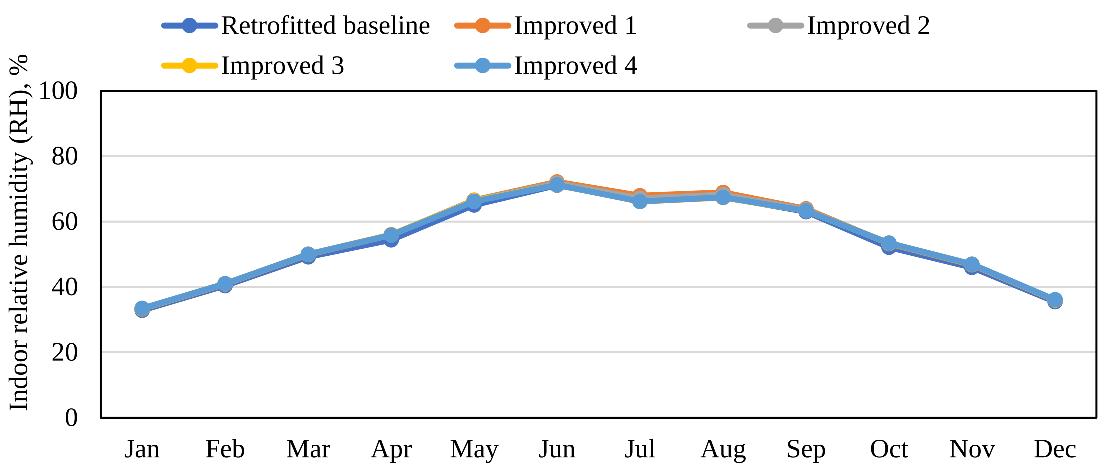


Figure 5-9: Comparison of monthly mean indoor relative humidity between the five retrofitted cases.

5.5.2. Indoor thermal condition comparison between the retrofitted and pre-retrofit cases

For the above-mentioned reason, the thermal condition of the retrofitted building was simulated with the improved retrofitting plan under scenario 4, and the results were compared with the thermal condition of the pre-retrofit building under the condition that the active heating and cooling systems were in operation. As shown in Figure 5-10, the indoor daily mean air temperature was compared between the retrofitted case and the pre-retrofit case. The temperature change of the retrofitted case and the pre-retrofit case were relatively stable, and the trends were similar because the heating/cooling system and its settings were the same in these two cases. However, due to the big difference in envelope insulation performance, the indoor temperature in these two cases were different. The retrofitted case had a more comfortable temperature which was around 18 ºC in January and 26ºC in July, this was about 2 ºC warmer and 1 to 2 ºC cooler respectively than the pre-retrofit case, and for this thermal condition, the heating and cooling energy consumption in the retrofitted case were only about 13% and 31% of which in the pre-retrofit case. Figure 5-11 shows the indoor daily mean relative humidity comparison between the retrofitted and pre-retrofit case. The change of relative humidity over the year in the retrofitted case and the pre-retrofit case with active heating and cooling were very close, with the value wave around 30% in winter and 60% in summer, and the value was only slightly lower in the winter months in the retrofitted case.

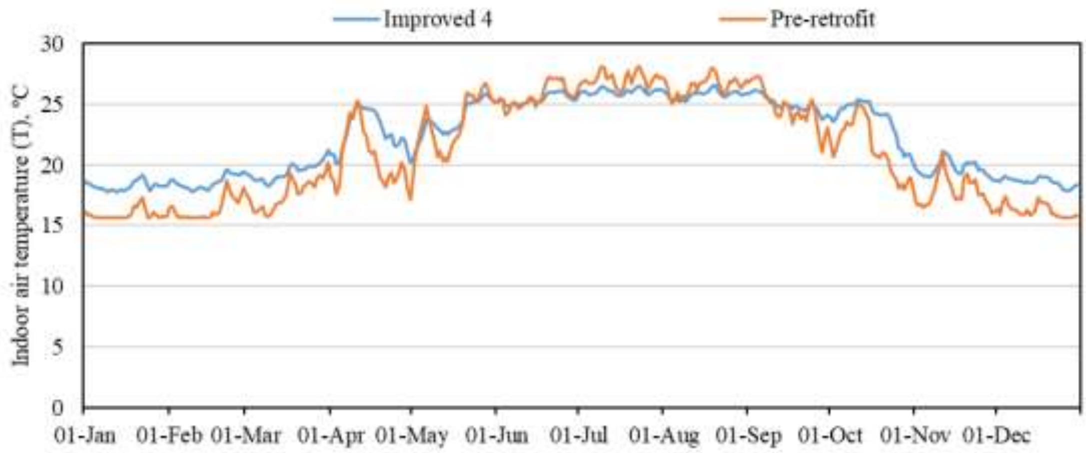


Figure 5-10: Comparison of daily mean indoor air temperature between retrofitted and pre-retrofit cases.

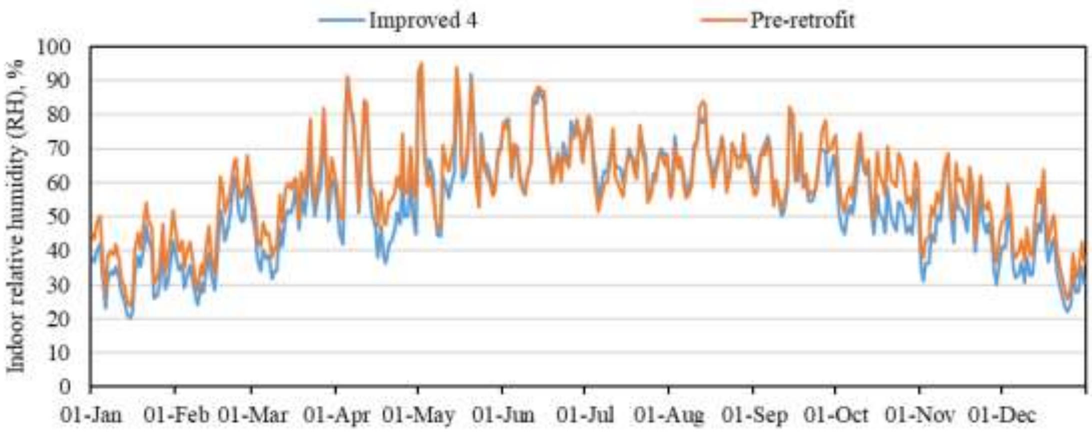


Figure 5-11: Comparison of daily mean indoor relative humidity between retrofitted and pre-retrofit cases.

5.5.3. Thermal comfort assessment through the PMV model

As mentioned earlier, the PMV model considers all six factors which influence the thermal feeling. The DesignBuilder dynamic simulations supported the four environmental factors used in the PMV model calculation of the retrofitted case, and the two personal factors of clothing insulation and metabolic rate were static values which were entered manually into DesignBuilder. Table 5-6 shows the DesignBuilder default settings for clothing level and metabolic rate for residential buildings, and Figure 5-12 illustrates the daily PMV results of the retrofitted case and the pre-retrofit case under this setting and under the same heating/cooling system. For the retrofitted case, as shown in Figure 5-12, most of the days in the winter months had a PMV result below -2, which was considered cold. For the summer time, most days had PMV results between 0 and -1, which was between neutral and slightly cool, and this level was usually considered relatively comfortable. For the pre-retrofit case, however, the PMV results suggested an even colder feeling in the winter time because the daily PMV results were mostly below -3 in winter, and thermal feeling in summer time was considered as warmer than the retrofitted case as the PMV results were between 0 and 1, but this level is relatively neutral with slightly warm feeling.

Moreover, both the retrofitted and pre-retrofit cases had several days (in April and May) where the PMV value was significantly lower than their surrounding days. This was mainly because of the combined effect from the sudden outdoor temperature drops on those days, and the clothing insulation which was switched from winter level to summer level from 1st April. For the days that had a comparatively low PMV result, their indoor temperature in those days were around 20ºC (retrofitted case) and 18ºC (pre-retrofit case). Similarly, the relatively high PMV results in the part of October could be explained on the same basis, as the outdoor temperature was still warm, but the clothing insulation was changed to winter level from this the first day of this month.

Table 5-6: DesignBuilder default clothing level and metabolic rate

Rooms	Clothing level	Metabolic rate
Bedroom	0.5 clo in summer; 1.0 clo in winter	0.8 met (90W/person)
Living room		1.0 met (110W/person)
Bathroom		1.1 met (120W/person)
Kitchen		1.4 met (160W/person)

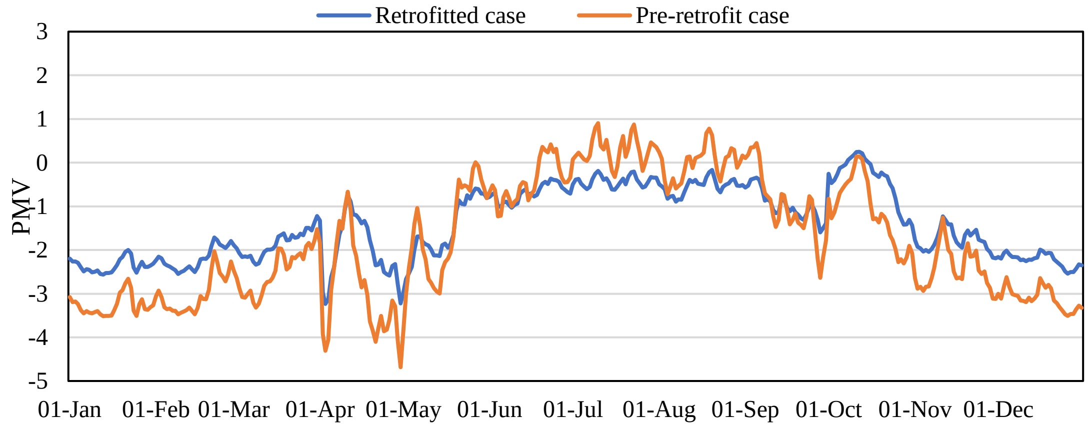


Figure 5-12: Daily PMV results of the retrofitted case

When the DesignBuilder default clothing level and metabolic rate were assumed for the occupants, most of winter time was assessed as cool by the PMV model. However, according to ASHRAE 55 (ASHRAE 55, 2017), the DesignBuilder default metabolic rates are slightly low and could be adjusted to slightly higher values as illustrated in Table 5-7. Moreover, one of the most direct methods to improve the cool thermal feeling is by adding clothing insulation, and according to the ASHRAE guild of clothing insulation, it was reasonable to improve the winter clothing level from 1.0 clo to 1.2 clo was by adding a thick sweater vest. Figure 5-13 demonstrated the PMV results of the retrofitted case under improved settings for metabolic rate and winter clothing level.

Table 5-7: Improved Clothing level and metabolic rate.

Rooms	Clothing level	Metabolic rate
Bedroom	0.5 clo in summer; 1.2 clo in winter	0.9 met (104W/person)
Living room		1.1 met (120W/person)
Bathroom		1.2 met (127W/person)
Kitchen		1.6 met (171W/person)

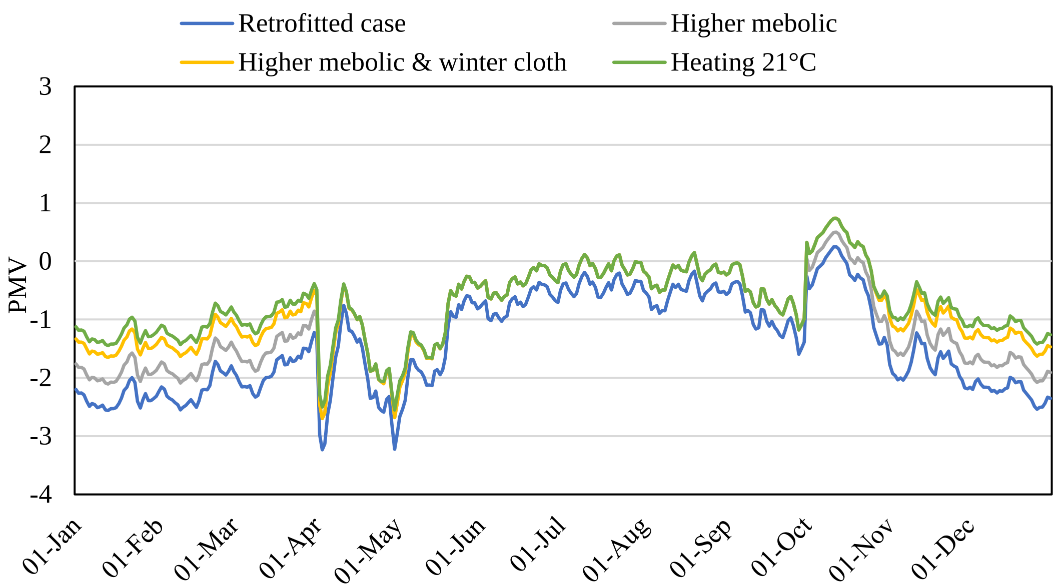


Figure 5-13: Daily PMV results of the retrofitted case under different situation.

As shown in Figure 5-13, an improvement in PMV was observed in winter after the slightly higher metabolic rate was set for the DesignBuilder calculation. In January, the lowest PMV improved from around -2.5 to -2, and the PMV result in summer increased around -0.5 to 0, which the comfort level was improved in both winter and summer. Then, the winter clothing level was improved to 1.2 clo based on the improved metabolic rate. As a result, the lowest PMV in January improved to around -1.5, and the summer PMV remained the same, as it was not influenced by winter clothing insulation improvement. Thus, a much better PMV result was assessed in winter because of the reasonable improvement in clothing insulation and metabolic rate, despite that most of winter time in the retrofitted case still experienced a slightly cool feeling based on the PMV results. To improve the winter thermal feeling in the retrofitted case by active method, the heating setpoint temperature was increased to 21ºC from 20ºC in the proposed retrofitting plan. However, the PMV result in winter months was only increased by a small scale (around 0.2 in PMV) as shown in Figure 5-13. An increase in heating set point temperature also led to greater heating energy demand, which increased from 14.9 kWh/m^{2}a to 17.5 kWh/ m^{2}a. This demand remained within the EnerPHit criteria, while this measure should not be suggested as efficient.

In conclusion, for the retrofitted case with adjusted metabolic rate and clothing level, the thermal comfort in winter months between November and March was evaluated as slightly cool as 78% of days in this range had PMV result lower than -1. The thermal feeling in the summer months should considered comfortable because the PMV results were mostly within the range between 0 and -1 and were closer to 0. For the days in April and May, that were evaluated as cool by the PMV model, the actual thermal feeling should be improved by adding more clothing insulation instead of the typical summer clothing calculated by DesignBuilder.

5.5.4. Thermal comfort assessment by the Passivhaus standard

Because the case building was retrofitted towards the Passivhaus EnerPHit standard, the indoor thermal comfort situation after retrofitting was also assessed against the Passivhaus standard, which considers indoor temperatures lower than 20ºC as cold, temperatures between 20ºC and 25ºC as comfortable, and temperatures above 25ºC as hot. Figure 5-14 illustrates the distributions of percentages of hours in the retrofitted case which are regarded as cold, comfortable, and hot by the standard.

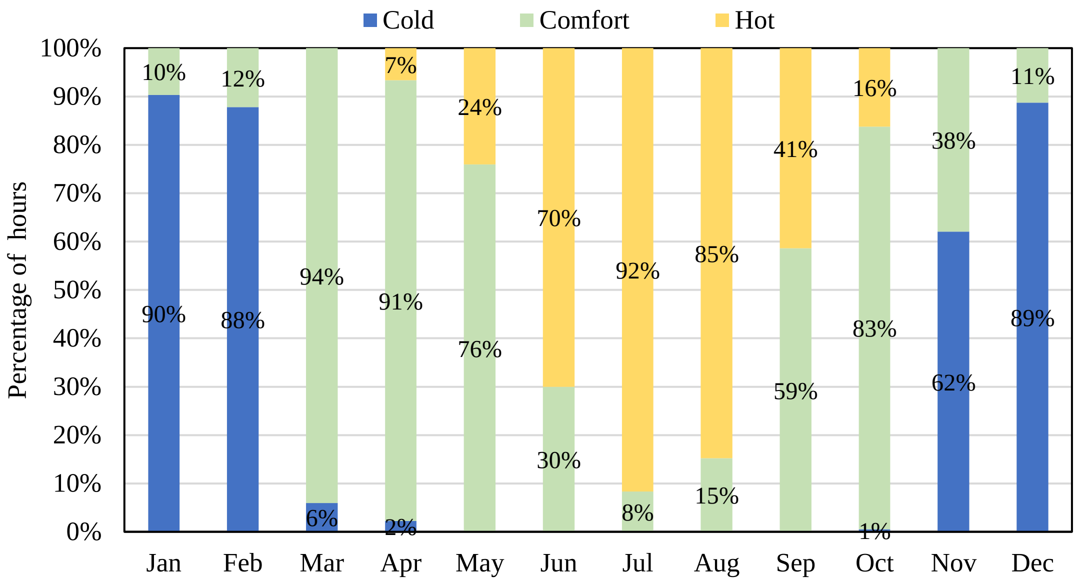


Figure 5-14: Percentages of hours which were regarded as cold, comfortable and hot in each month by the Passivhaus standard

Generally, most months failed to meet the comfort temperature requirement. The overcooling percentages of the months between November and February were quite high, especially in January, when 90% of the hours were considered cold. However, the daily mean temperature in January was 18.2℃, which is close to the required 20℃. Thus, although the indoor temperature throughout winter largely failed to meet the standard, it still should not be considered too cold. On the other hand, Figure 5-14 illustrates that overheating problems occur from April to October. July has the highest percentage of overheating, which was 92%, although the daily mean temperature in this month was 26.1℃.

Furthermore, March and April were observed as the most comfortable two months with 94% and 90% comfort percentages, respectively. For the whole year period, the percentages of the hours in which the air temperature level was considered as cold, comfortable and hot were 33.2%, 38.7% and 28.1% relatively. Therefore, by the Passivhaus standard, fewer than half of the hours within a yearlong period were not comfortable in the retrofitted case building, and the overheating and overcooling problem was of the similar degree. It is worth noting that the same indoor thermal condition had different evaluation results by different methods. For example, by the Passivhaus standard, the summer thermal condition in the retrofitted case was considered hot, while the PMV model assessed it as comfortable with slightly cool feeling. In general, the indoor thermal condition in the retrofitted building had been greatly improved compared to the pre-retrofit situation, and the retrofitted thermal condition should be considered as generally comfortable with acceptable discomfort observed in summer and winter.

5.6. Summary

This chapter has considered the possibility of retrofitting plans which enable a case building to achieve the Passivhaus EnerPHit standard energy efficiency while the material inputs could be decreased against a baseline retrofit plan. The first finding from this chapter was that the heating demand should be the dominant factor to be considered in retrofitting under the hot summer - cold winter climate, because it was found to be much more sensitive to the envelope thermal performance changes than the cooling energy demand, and higher thermal performances from all the tested parameters were needed to achieve the EnerPHit heating criteria than the cooling criteria. As a result, the retrofitting solutions should have a high insulation thickness in the external wall, followed by the roof and floor, and the interior floors were confirmed unnecessary to be insulated. The final proposed retrofitting plans for the case building under the different scenarios could all achieve the EnerPHit standard with a very similar level of energy savings of about 87% and 70% in heating and cooling, respectively, from the pre-retrofit condition. However, the retrofitting material inputs for achieving this energy saving were different in each retrofitting plan. The main reason for this was the performance changes in airtightness level and windows, as the better performance of those two factors could lead to a lower required thickness in envelope insulation. Overall, due to the arrangement of the retrofitting measures, each proposed plan ultimately achieved insulation materials reduction, with reductions between 18% and 58% compared to the baseline retrofit plan.

Finally, the indoor thermal comfort of the retrofitted case building was evaluated through the PMV model and the Passivhaus standard. After retrofitting, the simulated indoor monthly mean temperatures were 18.2°C and 26.1°C in January and July, respectively, which suggested a large improvement in thermal comfort compared with the pre-retrofit case. However, both the PMV model and Passivhaus standard suggested a slightly cool feeling in the winter time. The PMV model suggested a neutral to slightly cool feeling for summer time, while the Passivhaus standard considered the same thermal condition as overheated.

At this stage of the research, there were five retrofitting plans for the case building that could achieve the EnerPHit standard successfully, and some of them required less insulation material than others, therefore releasing less embodied carbon. However, reducing carbon emissions over the lifetime of a building is regarded as more meaningful. Thus, a life cycle carbon analysis of the proposed retrofitting plans will be carried out in the next chapter and a life cycle cost analysis because it is also a significant factor that affects the decision making of a retrofitting project.

Chapter 6. Life cycle analysis of the proposed retrofitting plans

6.1. Overview

Against the background of climate change and resource exhaustion, sustainable retrofitting of existing residential buildings has been widely accepted as a vital way to lower global energy consumption and greenhouse gas emissions in the building sector. The previous chapters discussed the energy saving possibilities of applying the Passivhaus EnerPHit retrofitting measures to the case building of this study, and the results showed that a large percentage energy saving could be achieved under all of the five proposed retrofitting plans when compared with the existing pre-retrofit case. In this chapter, the focus has been moved to assessing the environmental impact of the proposed retrofitting plans via a life cycle carbon analysis. Considering that cost would be a key factor in choosing a sustainable retrofitting plan, a life cycle cost analysis will also be carried out in this chapter to see if the deep Passivhaus retrofitting plans would have a cost benefit over a certain lifespan.

An EnerPHit standard deep retrofitted building is expected to be capable of operation for many years. However, for both the calculation of the life cycle carbon footprint and life cycle cost in this study, a relatively short life span of 30 years was applied, because 30 years was considered as a reasonable period in which to evaluate if the benefits from the proposed retrofitting plans can be achieved but not at the expense of a very long lifespan.

To assess the life cycle carbon and cost performance of the retrofitting plans, the scope of life cycle stages included in the carbon and cost calculation was decided firstly based on the available data source for each stage. Then, the future energy consumption of the case building under the different retrofitting plans was simulated in

DesignBuilder, with future weather files generated for the case region by Meteonorm, as this information is required for both operational carbon emission and cost calculation. Following this, the carbon emissions and costs in each of the life cycle stages under the retrofitting plans were calculated, and the total values over a 30 year lifespan were compared with the values of the existing pre-retrofit case in order to reveal the retrofitting carbon and cost payback time. Finally, the benefits from the different retrofitting plans were analysed and compared in a way that the cost and carbon emission in the assumed lifetime could be combined. This was done by analysing the difference in the cost of each tonne of carbon saved as a result of the retrofitting plans. Also, this method was used to evaluate the performance of each single retrofitting measure, as it would be useful to understand their benefits in term of both cost and carbon.

6.2. Scope of the life cycle analysis

The life cycle analysis was advanced for evaluating the environmental or monetary impact from each of the stages in a building's lifetime, and it helps with identifying the potential benefit from a certain design or retrofitting measure among its alternatives (Sierra-Pérez et al., 2018). The conclusion of a life cycle analysis could vary, based on the selection of the analysed life cycle boundaries (Dodoo & Gustavsson, 2013). The more stages in the building's lifetime that are included, the more comprehensive and accurate the analysed results could be. However, the decision of the boundary conditions usually depends on the limitation and availability of reliable data sources in each of the life cycle stages for a different country or region. Moreover, issues such as a different focus of the analysis and assumed operational lifetime could also directly affect the life cycle analysis result. The influence from the building operation or in use stage usually requires significant attention in many researches as energy consumption in this stage usually takes the largest share among the whole life cycle stages (Gustavsson & Joelsson, 2010). Nevertheless, more attention is focused on the influence of the product stage in which the building materials are manufactured from raw material extraction and processing, especially in the case of new builds and refurbishments aiming to achieve a very low operational energy consumption, as this could be achieved because a greater amount of building materials and products are used. Assessing the impact from construction and the end of life stage could be challenging for a comprehensive life cycle study, because their actual quantitative information is usually quite limited (Scheuer, Keoleian, & Reppe, 2003). Benefits from materials or components recycled from demolition could show the future resource efficiency of the current project, but the benefit should be accounted for into the next project when they are repurposed.

6.2.1. Scope of life cycle carbon analysis

In this study, as many stages in a building's lifetime as possible were included in the analysis boundary. Table 6-1 demonstrates a building's whole life cycle stages, based on sustainability of construction works framework in British Standard BS EN 15978, and these stages were included in this study. The product stage between stage A1 to A3 present the sum of carbon emissions for a product from mining the raw material (cradle), to the manufacturing as a finished product which is ready to be sent out from the factory (gate). This cradle to gate carbon emission is also frequently known as the embodied carbon of the product. The embodied carbon of all the materials and products proposed in the retrofitting plans in previous chapters were included in this life cycle carbon analysis, and the embodied carbon data were sourced from the software One Click LCA. The stage A4, transport, which represents the carbon emissions due to the delivery of the products from factory gate to building site, were also included in this study. The transport carbon data were also sourced from One Click LCA. The stage A5, the carbon emissions arising from all the construction related activities, was not included in this study because no reliable carbon data source was found for the case region, and it was difficult to accurately assume the quantity of construction activities and related energy consumption.

Table 6-1: The whole life cycle carbon stages and the scope of this analysis.

Stages	Include?	Scopes
A1-A3: Product stage	√	Embodied carbon of retrofitting related materials and products
A4: Transport	√	Transport carbon for delivering materials to building cite
A5: Construction	×	Out of scope due to no reliable data source.
B: In use	√	Heating and cooling carbon emission over the assumed lifespan, retrofitting products replacement
C: End of life	×	Out of scope due to no reliable data source.
D: benefits to future life cycle	×	Out of scope due to no reliable data source.

Furthermore, the stage B response for all of the carbon emissions associated with the operation of the building over its entire life cycle included all the energy usage, water usage, maintenance, replacement of building components. In this study, since the focus had been laid on the space heating and cooling energy conservation, the unregulated energy was assumed as the same in pre-retrofit and retrofitted cases – thus, only the carbon emissions due to space heating, cooling and retrofitting produces replacements were included in the life cycle analysis. The stages C and D, which refer to the emissions due to the all activities, such as demolition, at the end of a building's lifetime, and the potential environmental benefit from the material recycled from the demolished building, were not included in the scope of this study because no reliable data source was found for the case region, and also because the lifespan in this study was assumed as 30 years, which should be not the end of a building which has been retrofitted to the EnerPHit standard.

The life cycle carbon footprint of the case building was calculated by Equation 6-1, which was based on the RICS guidance (*RICS*, 2016) , but subtracted the life stages which were not considered into the analysis boundary. In addition, carbon dioxide (CO_2) is the main constituent greenhouse gas, but there are also other gases, such as methane and ozone. In this life cycle carbon footprint measurement, the standard unit of carbon dioxide equivalent (CO_2e) was used as it expresses the impact of different greenhouse gases in terms the amount of global warming potential that the equivalent carbon dioxide would cause.

$$LCCF = \sum_{i=0}^{i}(EC^i m^i + TC^i m^i d^i + RC^i) + \sum_{y=0}^{y} OC^y$$

Equation 6-1

where:

LCCF = life cycle carbon footprint, $kgCO_2e/m^2$

i = item of material

EC = embodied carbon value of material i, $kgCO_2e$

m = mass of material i, kg or m^2

TC = transport carbon value of material i, $kgCO_2e$

d = distance of transport for material i, km

y = year

OC = operational carbon in year y, $kgCO_2e$

RC = replacement carbon of material i, $kgCO_2e$

6.2.2. Scope of life cycle cost analysis

For the scope of life cycle cost, Table 6-2 illustrates the key cost categories based on RICS guidance (*RICS*, 2016) and the scope included in this study. The construction cost equivalent to the total development costs in the construction stage, and this includes many items such as site costs, construction cost, and labour costs. For this category, this study considered the total initial cost of the materials and products related to the proposed retrofitting plans, while other costs were not considered due to a lack of reliable cost data. Next, the renewal costs included the replacement of hard facilities and components incurred in ensuring the functional performance of the asset. This study considered the replacement of retrofitting related products due to end of technical service life. For the operation costs, which include all running utilities, rent, taxes and other fees associated with the building's operational stage, in this study, only the cost of space heating and cooling energy consumption were included, for the same reason as in LCCF calculation. Furthermore, the maintenance costs and end of life cost were not included in this study because no reliable data source was found for the case region.

Table 6-2: Key categories of life cycle cost analysis and the scope included in this study.

Categories	Include?	Scope
Construction costs	√	Initial cost of retrofitting related materials and products
Renewal costs	√	Replacement cost of retrofitting related products
Operation costs	√	Heating and cooling cost over the assumed lifespan
Maintain costs	×	Out of scope due to no reliable data source
End of life cost	×	Out of scope due to no reliable data source

The life cycle cost of the case building was calculated using Equation 6-2, which is shown below. The bank loan interest rate of 4.35% in China (*CEIC*, 2021) was used as the discount rate for the LCC calculation, so the total cost over the assumed lifespan could be calculated as net present value (NPV), which presents the future value in the current price.

$$LCC = \mathrm{IC} + \mathrm{RC} + \sum_{n=1}^{N} \frac{OC_t}{(1+r)^t}$$

Equation 6-2

where:

LCC = life cycle cost, ¥/m^2

IC = total initial cost, ¥/m^2

RC = total replacement cost, ¥/m^2

OC = operational cost, ¥/m^2

N = years of the assumed lifespan

t = number of the year

r = discount rate

6.2.3. The building cases for life cycle analysis

Table 6-3 illustrates the six cases which were included in the calculation scope. Because one of the aims of the life cycle analysis was to evaluate the carbon and cost payback time of the proposed retrofitting plans for the case building, the LCCF and LCC of the existing pre-retrofit case were required in order to make the comparison. The other five cases shown in Table 6-3 were the proposed retrofitting plans which enable the case building to achieve the EnerPHit energy standard. The retrofit baseline case was proposed in Chapter 4, based on a step-by-step retrofitting analysis, and the four improved retrofitting plans were suggested in Chapter 5 under different hypothetical scenarios. From the consideration of energy, the retrofit baseline case had the lowest yearly energy consumption, but this was achieved using a relatively high level of insulation material. The yearly energy consumption rates of the four alternative plans were very similar and higher than that of the retrofit baseline case, while they also had different requirements for insulation material, owing to the differences in the scenario hypotheses. The life cycle analysis was expected to evaluate the benefit of the five retrofitting plans from other significant perspectives associated with low-energy buildings, and thus a more comprehensive evaluation could be facilitated for the proposed plans.

Table 6-3: Building cases involved in life cycle analysis and their different in energy demand and thermal performance

		Pre-retrofit	Retrofit baseline	Improved 1	Improved 2	Improved 3	Improved 4
Heating demand (kWh/m^2a)		150.6	14.9	20.0	19.9	19.9	19.7
Cooling demand (kWh/m^2a)		42.0	11.5	12.6	12.4	12.2	12.2
Exterior wall	Ins* (mm)	0	250	300	250	225	175
	U* (W/m^2K)	2.32	0.125	0.105	0.125	0.138	0.175
Roof	Ins (mm)	0	250	250	175	175	100
	U (W/m^2K)	1.9	0.123	0.124	0.172	0.172	0.283
1st floor	Ins (mm)	0	250	250	150	100	75
	U (W/m^2K)	2.44	0.126	0.126	0.203	0.295	0.378
Interior floors	Ins (mm)	0	250	0	0	0	0
	U (W/m^2K)	2.44	0.126	2.44	2.44	2.44	2.44
Glazing	U (W/m^2K)	5.85	0.78	0.78	0.98	1.25	0.78
Airtightness (ach)		3	0.6	0.8	0.7	0.6	0.6

*Ins stand for insulation material thickness; *U stand for U-value.

6.3. Future energy consumption of the case building under different cases

The life cycle analysis for the case building was carried out for an assumed life span of 30 years and, according to the discussed analysis scope, the heating and cooling energy consumption values were required for calculation of both the carbon emission and costs during the 30 years operational time. Figure 6-1 demonstrates the DesignBuilder simulated yearly energy consumption of the case building in current and future years under the pre-retrofit condition and the five retrofitting plans. The future weather files for the case region for the years 2030, 2040 and 2050, as used in

DesignBuilder simulations, were generated by Meteonorm weather generator using the IPCC AVR4 A1B scenario, which considered a balanced situation of the technological changes in future energy systems (Ogunlade Davidson, 2014). Only Meteonorm version 7 was available at the time the simulations were done, whereas version 8 introduced scenarios based on Representative Concentration Pathways (RCP).

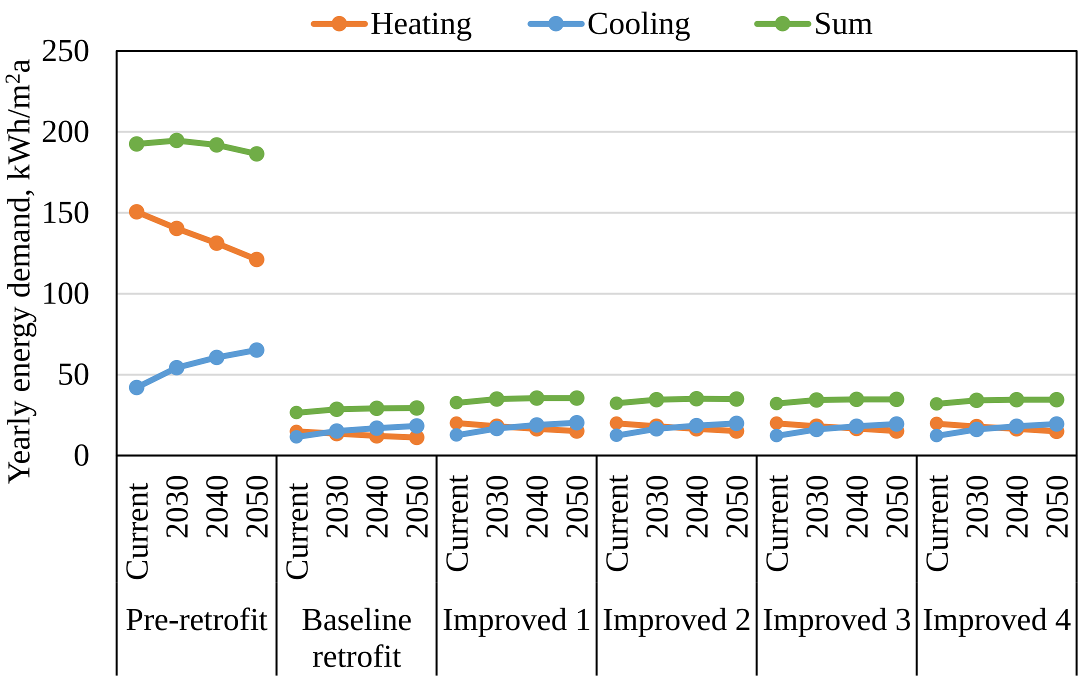


Figure 6-1: Future yearly energy demand of the case building under pre-retrofit and the five different retrofitted cases.

Under this balanced prediction of weather change, the simulated results indicated that the heating and cooling energy demands had an opposite trend over the time, which were to rise and fall respectively for all the pre and post retrofit cases. In addition, the total energy consumption of the pre-retrofit case went through a trend which first rose and then fell, while the five retrofitted cases were all predicted to have a stable and slow upward trend.

6.4. Life cycle carbon assessment

In this section, the carbon emissions from each of the considered life cycle stages of the pre-retrofit case and the five retrofitted cases are assessed in order to view the LCCF results and the carbon payback time of the proposed retrofitting plans.

6.4.1. *Embodied carbon of retrofitting plans*

Table 6-4 illustrates the embodied carbon data of the materials and products required for retrofitting, and as mentioned earlier, those data were sourced from the China database of the software One Click LCA. However, there are several products for which the software has no data for Chinese manufacture, thus generic data were used.

Table 6-4: Embodied carbon data of the retrofitting related materials sourced from software One Click LCA.

Materials	Embodied carbon	Database
Insulation material-Rockwool	1.31 $kgCO_2e/kg$	China data
MVHR system	1420 $kgCO_2e$/unit	
Air conditioning system	814 $kgCO_2e$/unit	
Electricity	0.87 $kgCO_2e/kWh$	
Window-triple glazed	80.4 $kgCO_2e/m^2$	Generic data
Window blinds	23.64 $kgCO_2e/m^2$	

For the insulation material of Rockwool, the source selected from One Click LCA has a density of 100 kg/m^3 and a thermal conductivity of 0.037 W/mK, which is the same density as with the Rockwool material used in DesignBuilder simulations, and the thermal conductivity was close with the value of 0.033 W/mK in DesignBuilder.

Table 6-5 demonstrates the breakdown of embodied carbon value for each measure under different retrofitting plans and their total embodied carbon. The carbon emissions of each retrofitting plan were converted to a function unit of $kgCO_2e/m^2$, which was divided by floor area (297m^2) of the retrofitted space, in order to stay uniform with the energy performance analysis in previous chapters, and also for convenience of comparison. The difference in total embodied carbon amounts between the proposed retrofitting plans were mainly because of the various amounts of insulation material used. For the retrofit baseline case, the simulated energy demand was lowest among other plans due to the adoption of relatively sufficient insulation material, thus the embodied carbon (99.33 kgCO_2e/m^2) was highest among them. Figure 6-2 shows the each of the single measures as a percentage of the total embodied carbon for each of the retrofitting plans. Rockwool insulation for exterior wall took the biggest share in all the five plans, and if the roof and floors are taken in account, the insulation material actually accounts for between 73% and 53% of the total embodied carbon of the five retrofitting plans.

Table 6-5: Breakdown of embodied carbon (EC) of each retrofitting plan.

	Retrofit baseline		Improved 1		Improved 2		Improved 3		Improved 4	
	Mass	EC ($kgCO_2e$)	Mass	EC ($kgCO_2e$)	Mass	EC ($kgCO_2e$)	Mass	EC ($kgCO_2e$)	Mass	EC ($kgCO_2e$)
Ex wall ins	7563 kg	9907	9075 kg	11888	7563 kg	9907	6806 kg	8916	5294 kg	6938
Roof ins	2238 kg	2931	2238 kg	2931	1566 kg	2052	1566 kg	2052	895 kg	1002
1st floor ins	2238 kg	2931	2238 kg	2931	1343 kg	1759	895 kg	1172	671 kg	752
In floor ins	4475 kg	5862	0 kg	0	0 kg	0	0 kg	0	0 kg	0
Windows	62 m^2	4985	62 m^2	4985	62 m^2	4985	62 m^2	4985	62 m^2	4985
Blinds	62 m^2	1456	62 m^2	1456	62 m^2	1456	62 m^2	1456	62 m^2	1456
MVHR system	-	1420	-	1420	-	1420	-	1420	-	1420
Sum	-	29502	-	25621	-	21588	-	20011	-	16857
Sum- by per m^2	-	99.33	-	86.27	-	72.69	-	67.38	-	56.76

Table 6-6: Yearly operational carbon emission (OC) converted from yearly operational energy consumption (OE) under current and future weather condition.

	Current		2030		2040		2050	
	OE kWh/m^2a	OC $kgCO_2e/m^2$	OEkWh/ m^2a	OC $kgCO_2e/m^2$	OE kWh/m^2a	OC $kgCO_2e/m^2$	OE kWh/m^2a	OC $kgCO_2e/m^2$
Pre-retrofit	190.6	165.8	192.7	167.6	191.9	167.0	186.4	162.2
Retrofit baseline	26.4	23.0	28.6	24.9	29.2	25.4	29.4	25.6
Improved 1	32.6	28.4	34.9	30.4	35.4	30.8	35.4	30.8
Improved 2	32.3	28.1	34.5	30.0	35	30.5	35	30.5
Improved 3	32.1	27.9	34.3	29.8	34.8	30.3	34.7	30.2
Improved 4	31.9	27.8	34	29.6	34.5	30.0	34.5	30.0

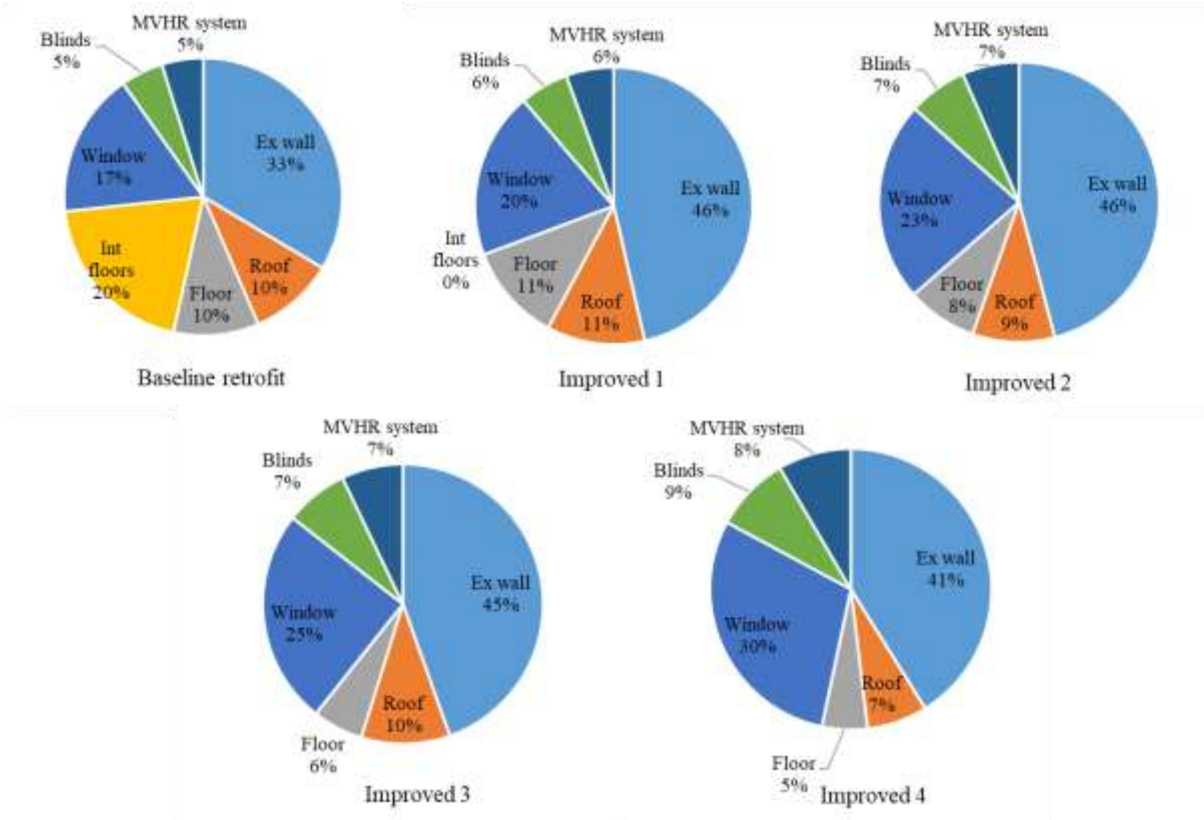


Figure 6-2: Embodied carbon percentage of each measure took in the five retrofitting plans.

It is therefore meaningful to highlight that selecting an insulation material with a low embodied carbon value would be a potential way of decreasing the environmental impact. One efficient way is to use organic insulation materials, such as cellulose insulation which is made mainly from recycled paper fibres. It has an embodied carbon value around 0.22 $kgCO_2e/kg$ and it is nearly six times lower than that of Rockwool. In addition, its thermal conductivity is around 0.04 W/mK, meaning that the thermal capacity is close to non-renewable traditional materials and relative good among renewable source materials (Zabalza Bribián, Valero Capilla, & Aranda Usón, 2011). However, cellulose has some uncertainties compared with traditional materials, such as moisture, fungal and setting problems which results in less use in market (Lopez Hurtado, Rouilly, Vandenbossche, & Raynaud, 2016). A case study in Finland suggested that replacing Rockwool with cellulose could achieve 15% saving in greenhouse gas emissions and embodied energy of the building envelope (Takano, Hughes, & Winter, 2014). In this study, Rockwool was originally selected in the retrofitting analysis because it is a commonly used insulation material in Chinese Passivhaus projects and is the most commonly used insulation materials in Chinese Passivhaus. It is a mineral material which has a comparatively high environmental impact. The environmental impact of Rockwool is actually relatively low compared with other traditional insulation materials; thus, it was decided not to replace Rockwool with an organic insulation material in this case study, in order to reflect carbon influence in the general situation.

6.4.2. Transport carbon

The amount of carbon emissions from transporting the retrofitting related materials from the factories gate to construction site in this life cycle analysis was calculated based on the One Click LCA database, which has a regional typical value for the transport distance and transport method for each product type. For insulation materials, One Click LCA considered they were transported by trailers that has 40 tons of capacity, and the distance was fixed to 60 km. The same transport type were considered for the windows and the related items, but with the distance of 380 km. It was assemed in One Click LCA that the MVHR system, was delivered by a truck with 9 tons of capacity, and the delivery distance was 320 km. Table 6-7 shows the One Click LCA calculated total transport carbon for the proposed retrofitting plans.

Table 6-7: Total transport carbon emission of each proposed retrofitting plan.

	Retrofit baseline	Improved 1	Improved 2	Improved 3	Improved 4
Transport carbon ($kgCO_2e$)	90.9	84.5	77.2	74	67.5
Transport carbon-Per m^2 ($kgCO_2e/m^2$)	0.31	0.28	0.26	0.25	0.23

6.4.3. Operational carbon

For the operational carbon emission during the assumed 30 years lifetime, a carbon conversion factor of 0.87 $kgCO_2e/kWh$ for electricity, which represents the current carbon emission for the electricity generated in China, was used to convert the yearly energy consumption of the pre and post retrofit cases to yearly operational carbon emissions. This carbon factor for electricity should be considered as the worst case scenario because the carbon emission should be decreased gradually with the improvement in the process of electricity generation in the future. Table 6-6 demonstrates the detailed value for each case under the current and futures weathers. Carbon emissions from mechanical systems replacement due to technical life ends in the assumed lifetime were included in the total operational carbon emission. For the pre-retrofit case, the air conditioning system has a technical lifespan of 15 years and would therefore need to be replaced in year 1 and year 16, as the current one has been functioning for 14 years. For the retrofitted cases, the MVHR system has a technical lifespan of 15 years as well and would need to be replaced at year 15. The value of emissions due to replacements is shown in Table 6-4.

A comparison between the total embodied, transportation and operational carbon under the pre and post retrofit cases is shown in Figure 6-3. The transport carbon could essentially be ignored when compared with other emissions in all the five retrofitting plans. The percentage of embodied carbon is slightly different among the five plans. It took about 11.9% in retrofit baseline plan as more insulation material was required in this plan, and the operational energy was lowest under this plan. For the other four improved plans, the embodied carbon took between 8.7% and 6.1%. Moreover, the operational carbon levels among them were quite similar as they each aimed to achieve an energy demand as close as possible with the EnerPHit standard requirement. For the pre-retrofit case, its operational carbon was about six times more than that in retrofitted cases, which was expected, as its energy consumption was higher than the retrofitted cases by large proportions, especially under the current weather condition.

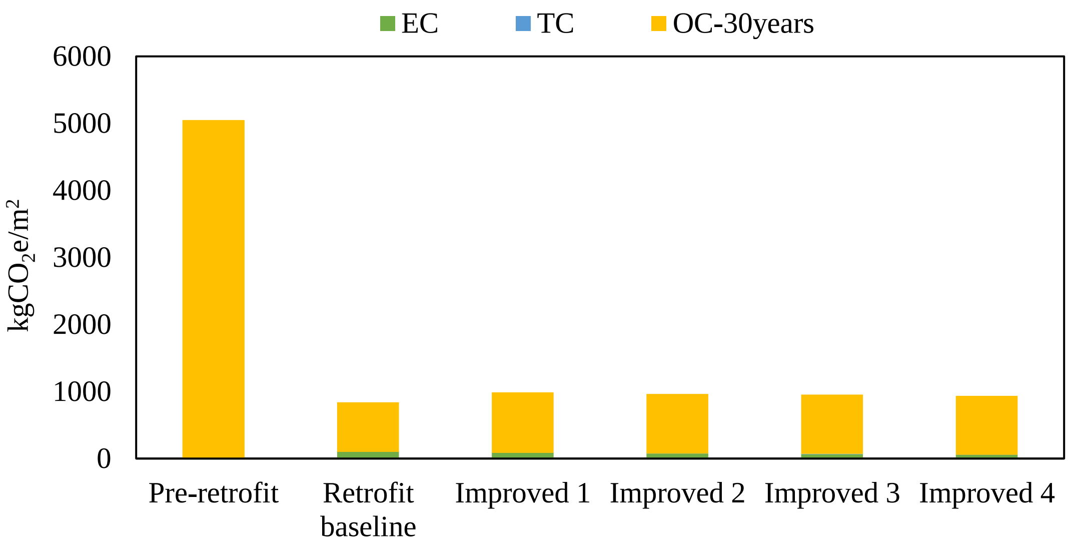


Figure 6-3: Comparison between Embodied (EC), transport (TC) and operational (OC) carbon in each case.

6.4.4. LCCF and payback time

Once the carbon emission in each of the life cycle stages had been calculated, the life cycle carbon footprints could be determined, as presented in Figure 6-4. From this figure, a clear upward trend can be seen in the footprint of the pre-retrofitted case when compared to the five retrofitted cases, which caused the footprints of five retrofitting plans to be quite similar. Because the yearly operational carbon of the pre-retrofit case

(165.8 $kgCO_2e/m^2$ for current climate) was much higher than the retrofit caused carbon emissions (99.3 $kgCO_2e/m^2$ for the case which had the highest embodied carbon), the carbon payback time of the retrofitting plans was only one year.

Table 6-8 lists the life cycle carbon emissions for each case, where, compared with the pre-retrofit case, a carbon saving around 83.4% to 80.5% could be achieved in the five retrofitting plans at the end of 30 years lifetime. Among the five retrofitting plans, the retrofit baseline case had the highest embodied carbon, while the life cycle carbon (837 $kgCO_2e/m^2$) was the lowest due to its low operational carbon. For the other four retrofitting plans, embodied carbon was the factor which determined the difference of life cycle carbon amount as the operational carbon were similar, and thus the improved plan under scenario 4 had the lowest life cycle carbon.

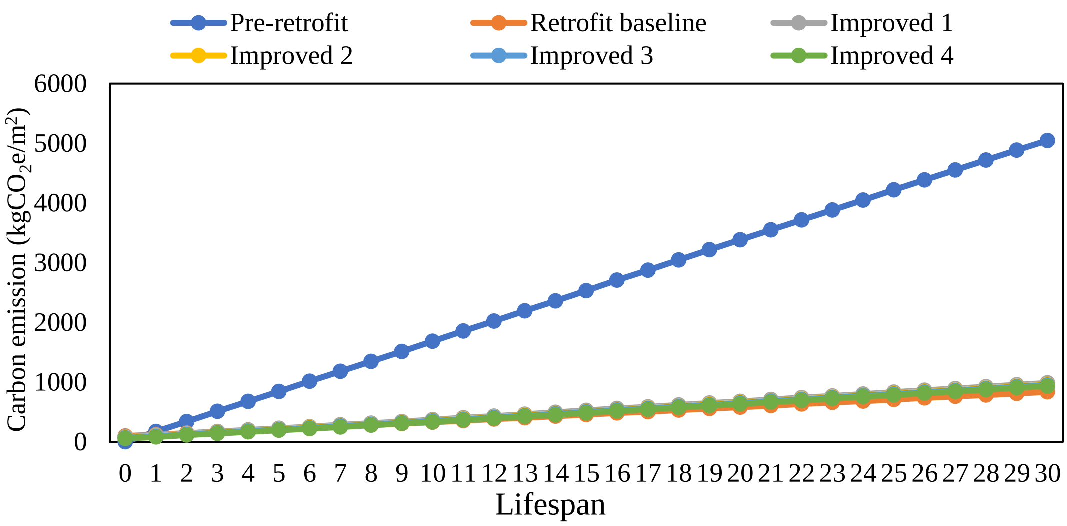


Figure 6-4: Life cycle carbon footprint of the pre and post retrofitted cases.

Table 6-8: Life cycle carbon result and payback time under different electricity carbon conversion factors (ECCF)

	China ECCF 0.87 $kgCO_2e/kWh$		UK 2020 ECCF 0.23 $kgCO_2e/kWh$	
	Life cycle carbon ($kgCO_2e/m^2$)	Payback time (years)	Life cycle carbon ($kgCO_2e/m^2$)	Payback time (years)
Pre-retrofit	5048	-	1354	-
Retrofit baseline	837	1	299	4
Improved 1	987	1	328	3
Improved 2	963	1	315	2
Improved 3	953	1	307	2
Improved 4	935	1	295	2

Furthermore, this study can highlight an issue which could heavily affect the LCCF analysis result. Operational carbon usually accounts for the largest share of the life cycle carbon, whilst the carbon emissions of the energy production source could change markedly over a building's lifetime. For example, Figure 6-5 illustrates the carbon conversion factor for the electricity which has been produced in the UK in recent years, where the value was dropped from 0.46 $kgCO_2e/kWh$ in 2015 to 0.23 $kgCO_2e/kWh$ in 2020 because of a decrease in coal use and increase in gas and renewable sources involved in electricity generation. Including this factor into the LCCF calculation in this study, the final life cycle carbon result was greatly changed, as shown in Table 6-8, in which the life cycle carbon results were around 2.7 to 3.7 times lower than the results calculated with China's electricity carbon conversion factor. Therefore, it is important to take the change of environmental impact from energy generation in the future into consideration, and the uncertainty from this issue could be lower if the carbon payback could be achieved in the early years after retrofitting is completed.

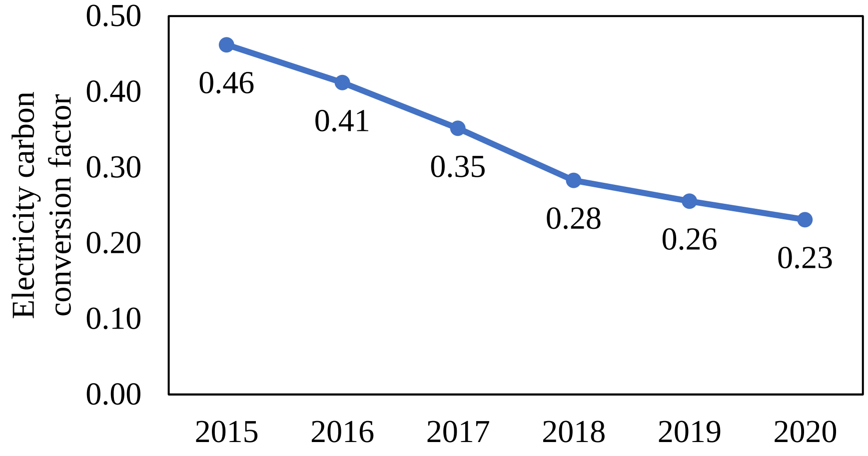


Figure 6-5: Carbon conversion factors for electricity produced in the UK in recent years (GOV.UK, 2021).

6.5. Life cycle cost assessment

In this section, the cost of the pre and post retrofit cases will be presented following the different life cycle stages in the planned scope of analysis, in which a binomial tree analysis is used to predict the local future electricity price for operational cost assessment. Then, the life cycle cost differences in each of the retrofitting plans and their cost payback time will be analysed.

6.5.1. Initial cost

Table 6-9 lists the unit price of the materials and products required by the proposed retrofitting plans and Table 6-10 gives the detailed cost breakdown for each of the retrofitting measures, and the total initial costs of the five retrofitting plans. Moreover, Figure 6-6 draws a comparison in initial costs for the different types of materials in each of the plans.

Table 6-9: Unite price of the retrofitting related products.

Products	Rockwool insulation	Passive windows	MVHR system	Exterior blinds shading	Shading controller
Unit price	250 ¥/m^3	U-value 0.8: 5280 ¥/m^2 U-value 1.0: 4953 ¥/m^2 U-value 1.2: 4626 ¥/m^2	60,000 ¥/each	380 ¥/m^2	630 ¥/each

Table 6-10: Cost breakdown of each retrofitting measures and the total initial cost of each retrofitting plans.

	Retrofit baseline (¥)	Improved 1 (¥)	Improved 2 (¥)	Improved 3 (¥)	Improved 4 (¥)
Exterior wall	18,906	22,688	18,906	17,016	13,234
Roof	5,594	5,594	3,916	3,916	2,238
1st Floor	5,594	5,594	3,356	2,238	1,678
Interior floors	11,188	-	-	-	-
MVHR	60,000	60,000	60,000	60,000	60,000
Windows	327,360	327,360	307,086	286,812	327,360
Shading, controllers	28,146	28,146	28,146	28,146	28,146
Sum	456,787	449,381	421,410	398,127	432,656
Sum/m^2	**1538.0** ¥/m^2	**1513.1** ¥/m^2	**1418.9** ¥/m^2	**1340.5** ¥/m^2	**1456.8** ¥/m^2

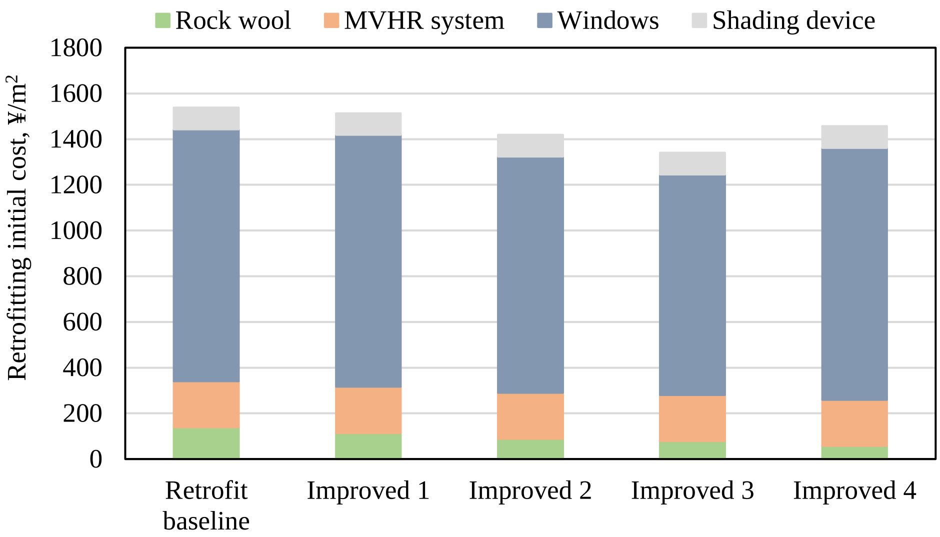


Figure 6-6: Initial costs of different retrofitting plans grouped by type of materials.

Among the retrofitting measures, the cost of the windows was the highest for all the five plans and accounted for about 72% to 76% of their total initial costs, which is very different with the carbon results, as windows only took 13% - 30% of the total embodied carbon. The cost of the MVHR system ranked second in all the five plans, between 13.1% and 15.1% of their total initial cost. The Rockwall insulation, which was applied to the whole thermal envelope and was the biggest material mass used in the retrofitting, accounted for more than half of the total embodied carbon, but the cost was only about 4% to 9% of the total initial cost depending on each retrofitting plans. The percentages in the total initial costs that the shading device accounted for in each plan was similar with the insulation material, between 6.2% and 7.1%. The total initial costs of the five retrofitting plans were between 1340.5 ¥/m^2 and 1513.1¥/m^2, and the improved plan 3 had the lowest initial cost because the window thermal performance was relatively lower than that in other plans and so the window cost was the lowest. This plan also required a comparatively small amount of insulation materials.

6.5.2. Electricity price prediction by binomial tree method

Energy consumption and the local electricity price were the two factors required to calculate the operational cost of the case building. The current and future years' energy consumptions were simulated by DesignBuilder while the future electricity price in Hunan province was the main uncertainty for this calculation. A binomial tree is a method that forecasts this uncertainty by analysing the possibility of future outcomes based on past data. In this case, more specifically, Hunan electricity prices in the previous 16 years, between 2005 and 2020, were used to calculate the volatility of price change, and then this volatility was employed to suggest the range of possible future electricity prices, which could be demonstrated by the divergence in a binomial tree diagram. However, it is important to note that the values predicted by the binomial tree were the range of possible outcomes and their probabilities rather than the actual values in the future (Ellingham & Fawcett, 2007).

Table 6-11 demonstrates the historical electricity prices, as well as the annual instabilities of the price change which were calculated from the difference between the average variation and each year's annual variation. Then, the instabilities were used to predict the volatility, a description of the amount of change over the time, by measuring their standard deviation. As shown in Equation 6-3, the volatility of electricity price change in Hunan was predicted to be 9%, and this suggested that the future prices could change both upwards and downwards with a frequency of ±9% annually.

$$\text{Standard deviation} = \sqrt{\frac{(9\%)^2 + (-21\%)^2 + (17\%)^2 + (10\%)^2 + (-11\%)^2 + \cdots + (-1\%)^2}{16-1}} = \pm 9\%$$

Equation 6-3

Table 6-11: Annual variation instability calculation of electricity price based on history prices

Years	Electricity price (¥/kWh)	Annual rate of change	Average annual rate of change	Instability
2005	0.503	-	1.4%	-
2006	0.556	10.5%		9.1%
2007	0.445	-20.0%		-21.4%
2008	0.528	18.7%		17.2%
2009	0.588	11.4%		9.9%
2010	0.530	-9.9%		-11.3%
2011	0.588	10.9%		9.5%
2012	0.588	0.0%		-1.4%
2013	0.588	0.0%		-1.4%
2014	0.588	0.0%		-1.4%
2015	0.588	0.0%		-1.4%
2016	0.588	0.0%		-1.4%
2017	0.588	0.0%		-1.4%
2018	0.588	0.0%		-1.4%
2019	0.588	0.0%		-1.4%
2020	0.588	0.0%		-1.4%

Figure 6-7 shows part of the binomial tree diagram for Hunan province, where the upward and downward price possibilities in future years are displayed by tree divergences. A full binomial tree diagram is demonstrated in appendix B. The expected values in each year were adopted in this study since those prices gathered all of the possible values in each year and weighted by their possibilities. The details of expected electricity prices for the assumed building lifespan of 30 years in the future are listed in Table 6-12.

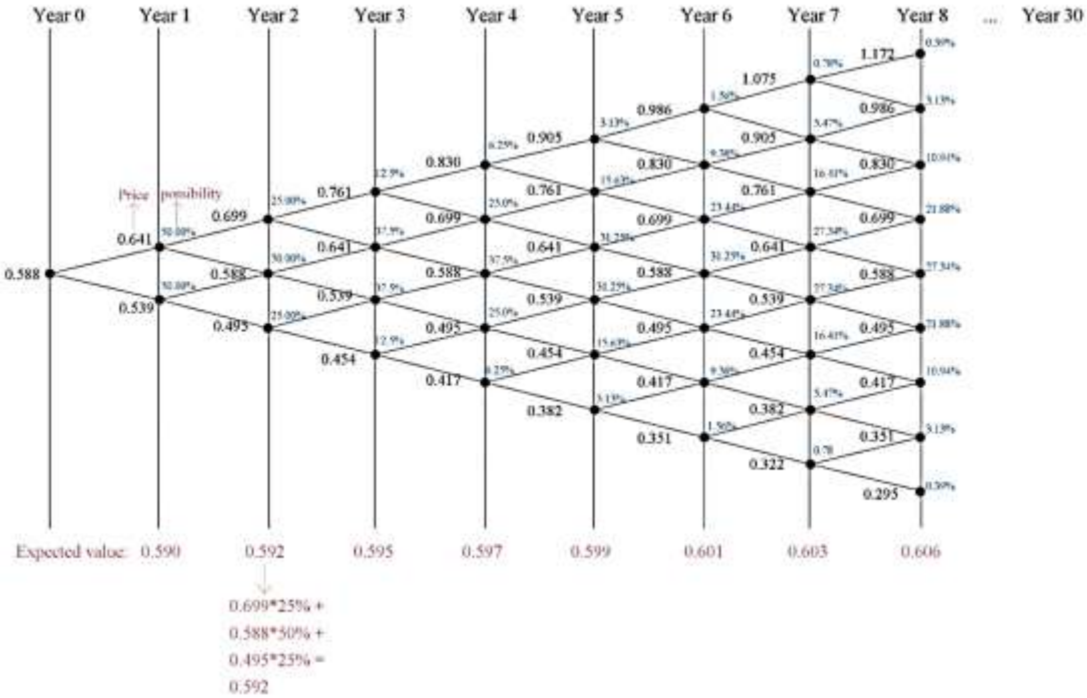


Figure 6-7: Binomial tree of Hunan electricity prices in future years.

Table 6-12: Expected electricity prices for 30 years in the future.

Year	Price(¥/kWh)	Year	Price(¥/kWh)	Year	Price(¥/kWh)
1	0.590	11	0.612	21	0.636
2	0.592	12	0.615	22	0.638
3	0.595	13	0.617	23	0.640
4	0.597	14	0.619	24	0.643
5	0.599	15	0.622	25	0.645
6	0.601	16	0.624	26	0.648
7	0.603	17	0.626	27	0.650
8	0.606	18	0.629	28	0.652
9	0.608	19	0.631	29	0.655
10	0.610	20	0.633	30	0.657

6.5.3. Operational cost

As mentioned in section 6.3, net present values (NPV) were used to present the operational costs over a 30 year lifetime so that the cost impact of the retrofitting plans could be analysed based on the current monetary value. Figure 6-8 and Figure 6-9 demonstrate the yearly operational cost of the cases before and after retrofits, under a situation in which no discount rate was applied, and when a discount rate of 4.35% was applied, so the latter figure shows the NPV. In comparing the two figures, a clear difference can be seen, especially for the pre-retrofit case, where the yearly operational costs showed an upward trend when the discount rate was not applied, since the electricity price was predicted to go upwards over the time. A certain drop occurred in year 30, and this was because the simulation weather file was changed from 2040 to 2050, which had a warmer climate, and the heating energy demand decreased and eventually led to a lower yearly energy cost. On the other hand, the trend of NPV of the operational cost was downward since the rate of currency depreciation is much faster than electricity price rises. For the NPV of yearly operational cost, the case with the baseline retrofit plan was the lowest since the initial cost for retrofitting was the highest, and the value of cases with the improved retrofitting plans were basically the same because of they were all targeted to exactly meet the energy criteria. However, the NPV of the pre-retrofit case was much higher than the retrofitted cases - it was estimated to more than five times higher than any of the retrofitted case even after the currency had been depreciating for 30 years.

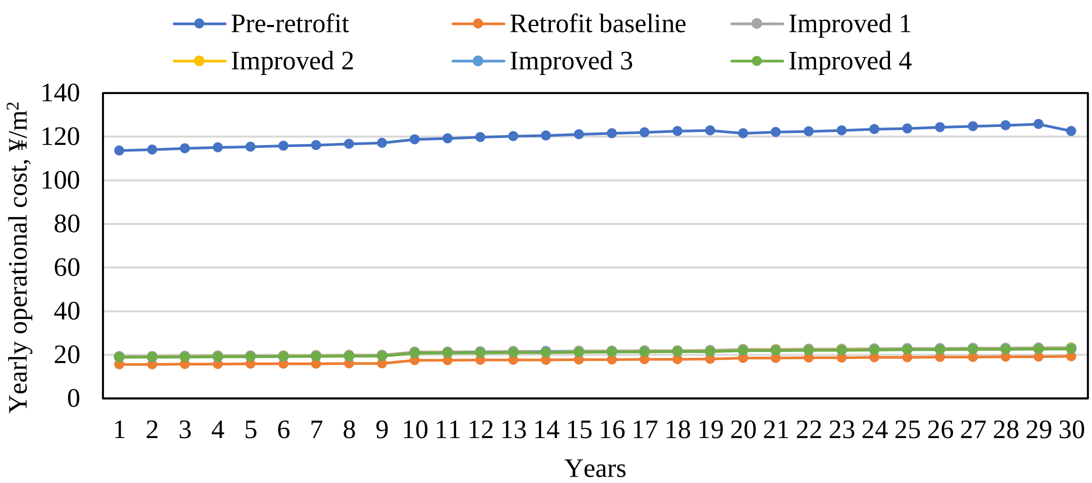


Figure 6-8: Yearly operational cost of the cases when discount rate was not applied.

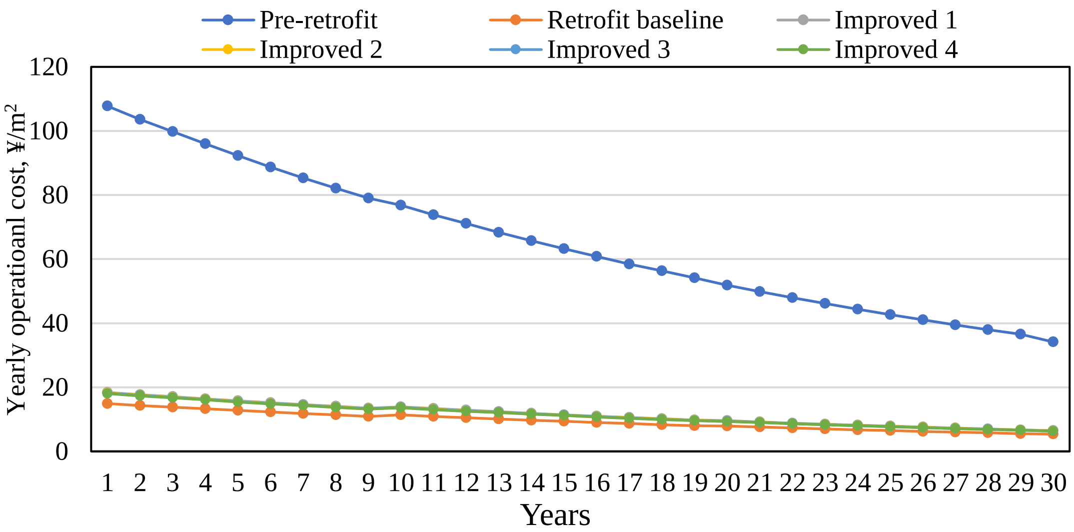


Figure 6-9: Yearly operational cost (NPV) of the cases when discount rate of 4.35% was applied.

6.5.4. Replacement cost

Products replacement due to technical life ends was considered in the life cycle cost assessment of the case building, Table 6-13 illustrates the costs of the items which need to be replaced during the assumed building lifetime. The MVHR system and air conditioning system both had a technical life of 15 years, so the MVHR system would need to be replaced at year 15 for the five retrofitted cases and the air conditioning system would need to be replaced at year 1 and 16, since the current one is already in its end of service time. A filter is a consumable for MVHR system operation and need to be replaced every four years based on BCIS component life expectancy guidance (*BCIS*).

Table 6-13: Cost of the items which need to be replaced.

	MVHR system	MVHR system filter	AC system
Replacement cost	60000 ¥	550 ¥	43500 ¥
Replacement cost by m^2	202 ¥/m^2	1.85 ¥/m^2	146.5 ¥/m^2

6.5.5. LCC and cost payback time

In this section, the total life cycle cost over a 30 year lifespan for the cases before and after retrofit are calculated and compared. As shown in Figure 6-10, the total costs were presented by NPVs, and a different trend can be clearly seen between the pre-retrofit and the five retrofitted cases. Because the upwards trend of the pre-retrofit case was greater, its cost exceeded all the five retrofitted cases at the end of the life cycle, which suggested that all the five proposed retrofitting plans could payback in monetary value. Table 6-14 shows the time in years required for each of the plans to attain monetary payback, of which the improved plan 3 had the fastest payback period of 20 years and the improved plan 1 had the slowest payback period of 24 years.

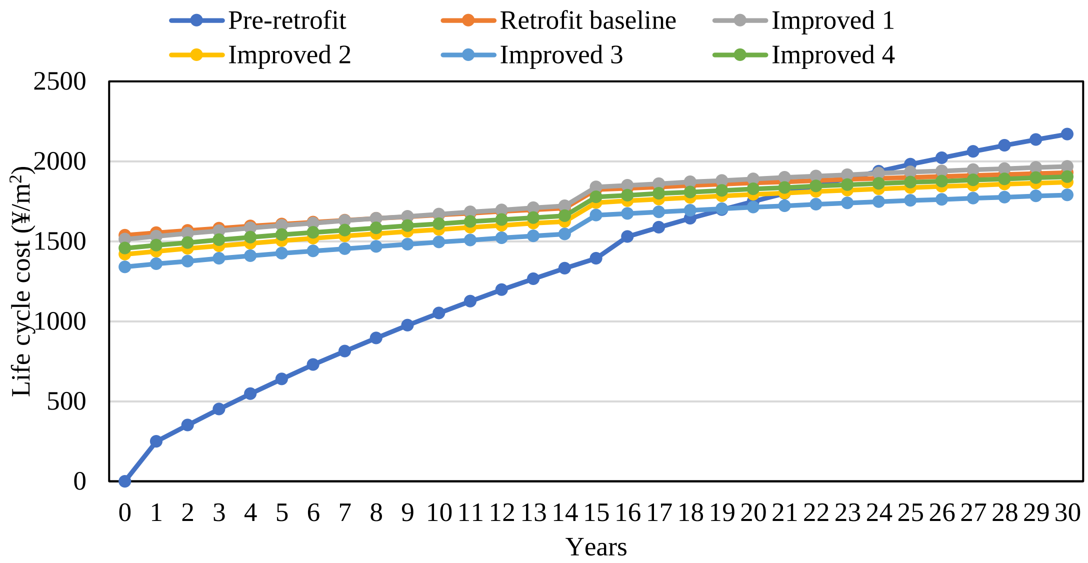


Figure 6-10: Life cycle cost of the pre and after retrofitted cases by NPV.

Table 6-14: Cost payback time of the case building with different retrofitting plans.

	Retrofit baseline	Improved 1	Improved 2	Improved 3	Improved 4
Payback time	23 years	24 years	22 years	20 years	22 years

The main factor that alters the payback period of the proposed retrofitting plans was the amount of initial cost. As shown in Figure 6-11, the retrofitting initial costs, as a percentage of the whole life cycle costs, were quite high, between 75% and 80% for all the plans. The operational costs of the four improved retrofit cases were similar, all around 18% of the total cost. Only that of the retrofit baseline case was relatively lower, which took 15% of the total cost. Moreover, the replacement costs of the retrofitting plans were all 107 ¥/m^2 and only took a small percentage from the total cost. Therefore, the difference in initial cost largely determined the difference in total life cycle cost of the retrofitted cases.

Furthermore, a large difference in operational cost between the pre-retrofit and retrofitted cases could be seen in Figure 6-11, in which the amount of pre-retrofit case was almost seven times higher than that of the retrofit baseline case, and nearly six times higher than that of the four improved cases. By comparing the total life cycle costs, the pre-retrofit case was expected to cost 2170 ¥/m^2 in the calculated lifespan, and about 18% to 9% of this cost could be saved by applying the proposed retrofitting plans. Improved plan 3 had the best economic saving, since its initial cost was lowest by adopting a relative lower thermal performance of triple glazed window. In general, the cost of EnerPHit retrofitting plans for the case building could be recovered, but only over a long time span, especially when compared with the carbon payback time, which was just one year for all the proposed plans.

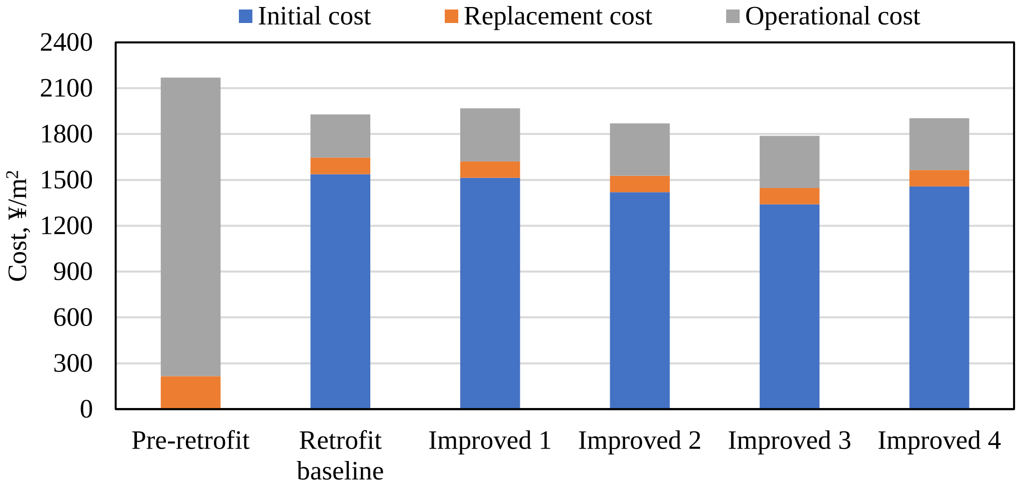


Figure 6-11 : Cost comparison in different life cycles for the pre and after retrofitted cases.

6.6. Cost of carbon reduction due to the retrofitting measures

In previous sections, the life cycle benefits of the proposed five retrofitting plans were analysed from the two aspects of carbon and cost, and their benefits were quite different from different points of view. Therefore, this section aims to analyse the retrofitting plans through a method that evaluates the cost of carbon reduction due to the application of retrofitting over a certain building lifespan so that the efficiency of carbon and monetary savings resulting from each plan could be combined in analysis and, accordingly, the different retrofitting plans could be compared in a relative fair way. This method is based on an evaluation indicator called the ‘Cost of each Tonne of Carbon Saved (CTS), in which the concept was to use the ratio between the extra costs and carbon conservation incurred by implementation of retrofitting measures within a certain life cycle period to access the cost of reducing per tonne of carbon emission. Therefore, the smaller the ratio, the lower the cost investment is required for reducing each tonne of carbon emission achieved by the retrofitting measures. The concept of CTS was proposed in the CIBSE technical symposium (Sweetnam & Croxford, 2011), but the authors did not consider the possible changes in building energy consumption due to climate change and the currency inflation during a building’s life time. This study tried to form a more detailed consideration by including those two factors and also the retrofitting products replacements due to technical lifetime end. The way CTS (¥/tCO_2) was calculated in this study is listed below from *Equation 6-4* to Equation 6-6. To be consistent with previous sections, the CTS of each the proposed retrofitting plans was measured in a lifespan of 30 years.

CTS (¥/tCO_2e) = Lifetime cost (¥) / Carbon saved (tCO_2e)

Equation 6-4

Lifetime cost (¥) =
Retrofitting initial cost – Discounted lifetime operational cost (pre-retrofit – retrofitted)

Equation 6-5

Carbon saved (tCO_2e) = Life time carbon (pre-retrofit case – retrofitted case)/1000

Equation 6-6

In addition, reducing the carbon emissions into the environment is one of the main drivers for governments to implement energy-saving measures to buildings. The cost is usually a high priority that the government or any interested party would consider when carrying out large-scale retrofits, and thus the retrofitting measures which reduce carbon emissions by lowering costs would have higher priority attached in retrofitting projects. For this reason, the CTS was identified for each of the individual retrofitting measures considered for the case building to achieve the EnerPHit standard. The individual measure of the retrofit baseline plan was considered for investigation because this retrofitting proposal was proven to have the best energy-saving efficiency among the others considered in the previous chapter. However, it is important to remember that the reasonable cooperation between different measures is the reason that extremely low building energy consumption could be achieved, rather than by certain individual measures alone. Therefore, if the CTS performance of a certain individual retrofitting measure was higher than that of a whole retrofitting plan, it means its efficiency in terms of cost to carbon was better, rather than that more carbon emissions could actually be reduced by increasing the cost investment to this measure.

6.6.1. CTS of the proposed retrofitting plans

In this section, the CTS performance levels of the five proposed retrofitting plans were identified, as shown in Table 6-15, where the calculation process is demonstrated. The lifetime cost identified the net present value in which the retrofitting initial cost offsets the savings in 30 years operational period due to retrofitting (replacements costs included). The lifetime cost of all the five plans were all negative, which suggested that the cost saved in the operational period was more than the initial cost, and so there were overall savings achieved by implementing the retrofitting plans in the considered lifetime. Plan 3 had the highest comparative lifetime cost saving. On the other hand, the carbon saved represents the emissions saved in the 30 years life cycle because of retrofitting. If this value is negative then the retrofitting plan has actually failed to achieve carbon reduction and, therefore, the meaning of evaluating the cost of reducing emissions is lost. For the five proposed plans, the efficacy of reducing carbon emissions was similar, all with more than 4 tonnes of carbon saved.

Table 6-15: Lifetime cost, carbon saved and the CTS of each proposed retrofitting plan with a 30 years lifespan considered.

	Pre-retrofit	Retrofit baseline	Improved 1	Improved 2	Improved 3	Improved 4
Initial cost (¥/m^2)	0	1538.0	1512.1	1418.9	1340.5	1456.8
Operational cost (¥/m^2)	2185.7	391.0	454.8	451.1	448.9	446.6
Lifetime cost (¥/m^2)	**-**	**-256.7**	**-217.9**	**-315.7**	**-396.3**	**-282.4**
Embodied carbon (CO_2e/m^2)	0	99.3	86.3	72.7	67.4	56.8
Operational carbon (CO_2e/m^2)	5047.9	737.9	900.4	890.7	885.4	878.5
Carbon saved (CO_2e/m^2)	-	4210.7	4061.3	4084.5	4095.1	4112.7
Carbon saved (tCO_2e/m^2)	**-**	**4.21**	**4.06**	**4.08**	**4.10**	**4.11**
CTS (¥/tCO_2e)	**-**	**-60.97**	**-53.65**	**-77.29**	**-96.78**	**-68.66**

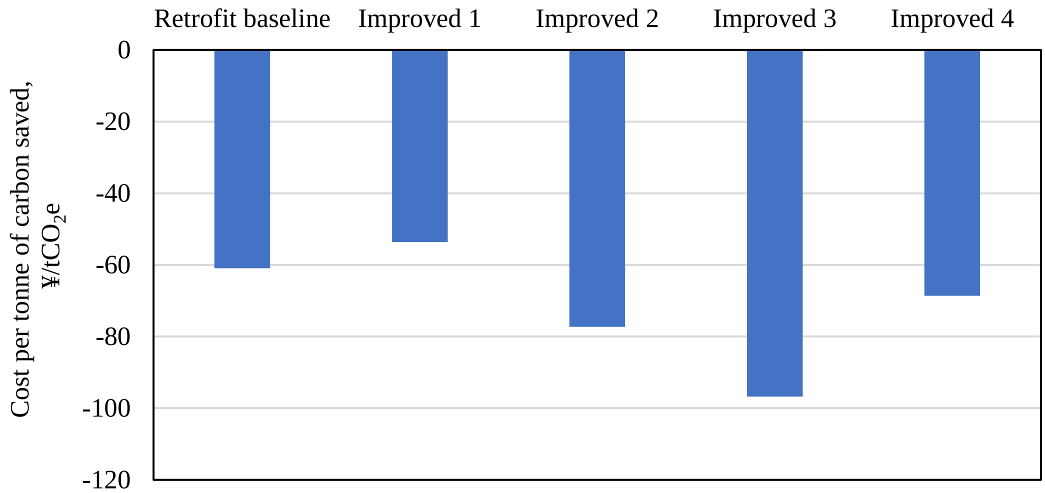


Figure 6-12: Difference in cost of each tonne of carbon saved (CTS) due to different retrofitting proposals.

Next, the CTS performance of the five plans was calculated, and their difference is also demonstrated in Figure 6-12. Because the amounts of carbon saved by the plans were similar, the differences in CTS were mainly attributable to their different lifetime costs. All the five plans had a negative CTS result owing to their negative lifetime cost. This result suggested that they all had achieved monetary savings while achieving carbon emission reductions in the considered lifetime, yet their monetary savings for each tonne of carbon saved were different. By comparing the CTS results of the five retrofitting plans it could be seen that Plan 3 had the highest benefit in terms of both cost and carbon, as when each tonne of carbon saves, a cost saving of ¥96.78 could be made at the same time, and the cost saving in terms of carbon in the other plans were lower, between 53.65 and 77.29 ¥/tCO_2e.

6.6.2. CTS of the individual retrofitting measures

This section attempts to assess the CTS performance of each individual retrofitting measure. Firstly, the energy consumptions when the case building only had a single retrofitting measure applied were simulated by DesignBuilder, under the current and future years' weather conditions. Figure 6-13 demonstrates the simulated results for each of the individual measures. From this figure, an overall trend is clearly apparent in which the energy consumption basically dropped slightly following the climate changes, when each of the considered single measures had been applied to the pre-retrofit case individually. Moreover, when compared with the pre-retrofit case, the yearly energy consumptions were lower no matter which of the measures were applied, while the yearly energy consumption was the lowest when the measure of exterior wall insulation was adopted.

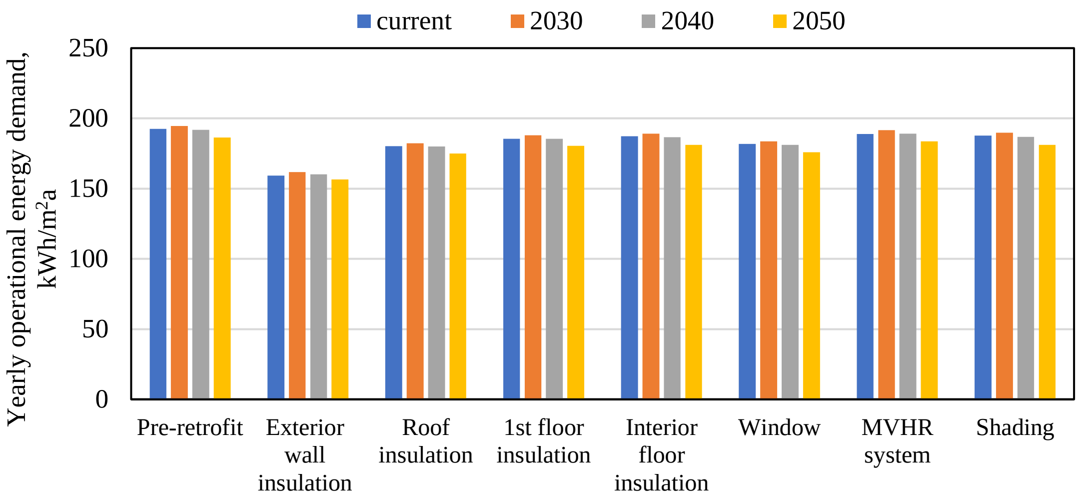


Figure 6-13: Yearly energy consumption of the cases when each retrofitting measures were applied individually, under the current and future years' climate condition.

After the operational energy consumption data were simulated, the corresponding operational costs and carbon emissions could be calculated. The replacements within the lifespan were considered in the same way as in life cycle analysis of the retrofitting plans earlier in this chapter. The initial cost and embodied carbon for each of the retrofitting measures were collected and demonstrated in previous sections, as shown in Table 6-10 and Table 6-5.

With this information, the life cycle cost (LCC) and life cycle carbon footprints (LCCF) of the individual retrofitting measures could be calculated and are shown in Figure 6-14 and Figure 6-15. By demonstrating the LCC and LCCF, the differences in initial retrofitting cost/carbon and operational cost/carbon between the pre-retrofit case and the cases that applying each of the single measures could be discerned.

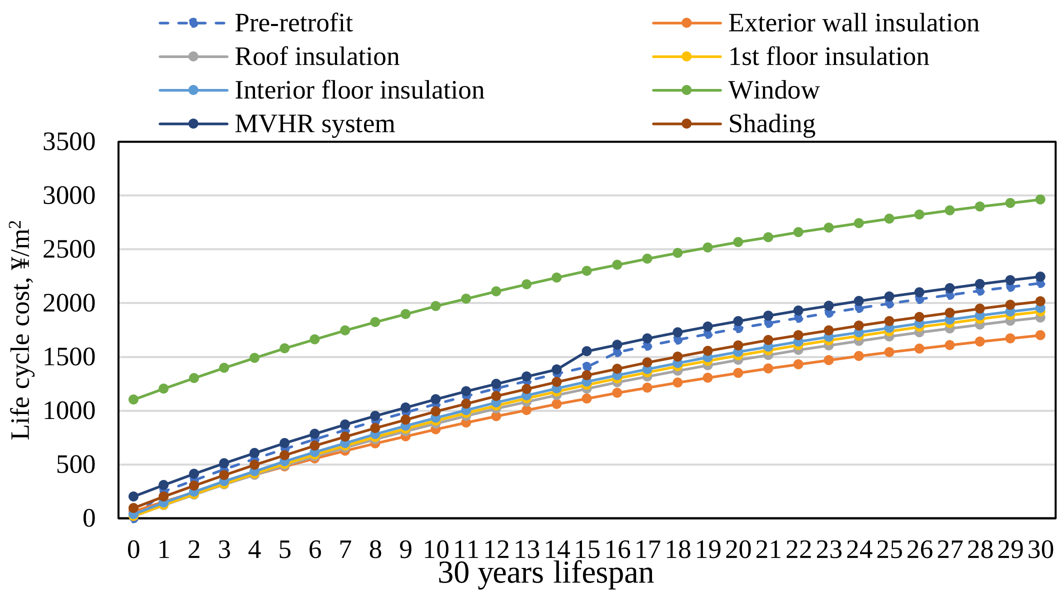


Figure 6-14: Life cycle cost of the case building when each measure was applied individually, value presented by NPV.

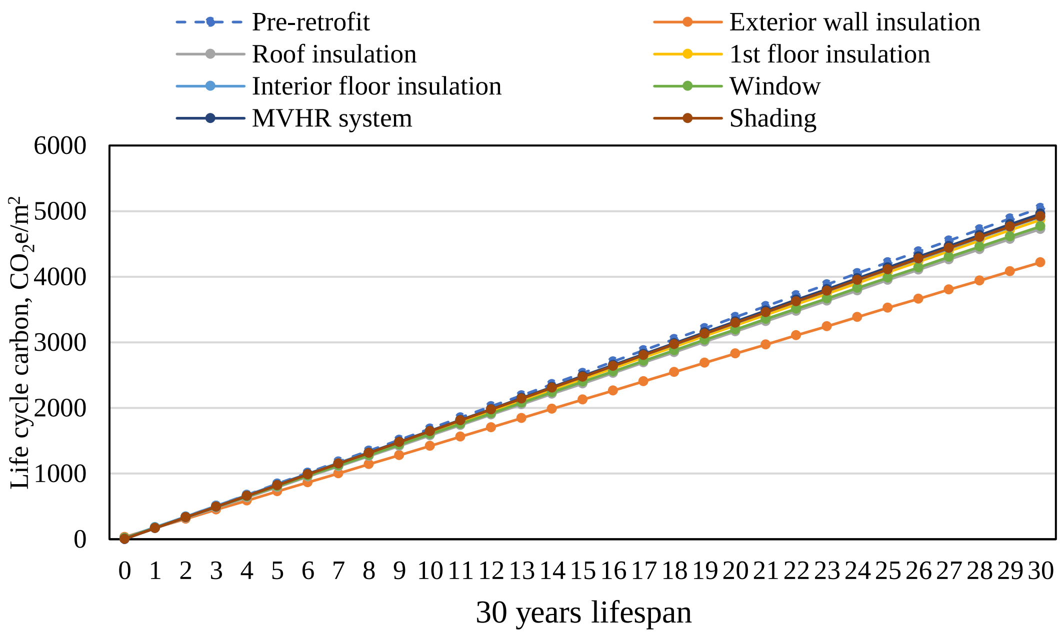


Figure 6-15: Life cycle carbon footprints of the case building when each measure was applied individually.

For the LCC, most of the measures were able to attain certain paybacks within the 30 year lifespan, because their initial costs were quite low and achieved a lower yearly operation cost than that of the pre-retrofit case. The exceptions were the two measures of triple glazed window and MVHR system, for which the initial costs were substantial and, therefore, failed to pay back in the lifespan. On the other hand, all of the single measures had achieved carbon paybacks since their embodied carbon levels were quite low even when compared with just one year's operational carbon. The reason for the difference in the life cycle carbon emissions of each measures was more due to the operational carbon in each year. The measure of exterior wall insulation was the one which resulted in the lowest yearly energy demand among the other achievable measures, and thus this measure had the lowest amount of carbon emission in this lifespan.

With the LCC and LCCF results available, the factors needed for identifying the CTS performance of each retrofitting measures were gathered conveniently and are demonstrated in Table 6-16. When comparing the total operational costs in a 30 year lifespan between the pre-retrofit case and the cases that had a retrofitting measure applied, the savings from most of the measures were enough to cover their initial costs. So, overall, they helped with monetary savings and their lifetime costs were negative. However, the lifetime cost of the measures of adopting high performance windows and MVHR system were positive, since their initial costs were dramatically high and were less likely to be paid back at all. An extended lifespan of 100 years was calculated for those two measures and their life cycle cost was still obviously higher than the pre-retrofit case, although the cost payback times of other measures were just one year. In terms of carbon emissions, the indicator of carbon saved was positive for all the measures, since the amounts of carbon saved from applying the measures in the operational stage were greater than their embodied carbon. Also, the carbon payback time was short for all the measures, only between one to three years. This was because their embodied carbon was quite low even compared with the amount in just one operational year.

Table 6-16: Lifetime cost, carbon saved, payback time and CTS of each individual retrofitting measures with a 30 years lifespan considered

	Pre-retrofit	Ex wall ins	Roof ins	1st floor ins	Int floor ins	Wind-ows	MVH-R	Shadi-ng
Initial cost (¥/m^2)	0	63.7	18.8	18.8	37.7	1102.2	202.0	94.8
Operational cost (¥/m^2)	2185.5	1636.7	1847.6	1901.3	1916.1	1860.2	2044.4	1920.8
Cost payback time	-	1 year	1 year	1 year	1 year	>100 years	>100 years	1 year
Lifetime cost (¥/m^2)	**-**	**-485.1**	**-320.1**	**-265.4**	**-231.8**	**776.9**	**60.8**	**-170.0**
Embodied carbon (CO_2e/m^2)	0	33.4	9.9	9.9	19.8	16.9	4.8	4.9
Operational carbon (CO_2e/m^2)	5047.5	4217.8	4726.9	4867.4	4912.3	4767.3	4957.4	4921.9
Carbon payback	-	1	1	1	3	2	1	1
Carbon saved (CO_2e/m^2)	-	829.7	320.6	180.1	135.2	280.2	90.0	125.6
Carbon saved (tCO_2e/m^2)	**-**	**0.83**	**0.32**	**0.18**	**0.14**	**0.28**	**0.09**	**0.13**
CTS (¥/tCO_2e)	**-**	**-574.7**	**-998.2**	**-1473.8**	**-1713.8**	**2772.6**	**675.8**	**-1353.8**

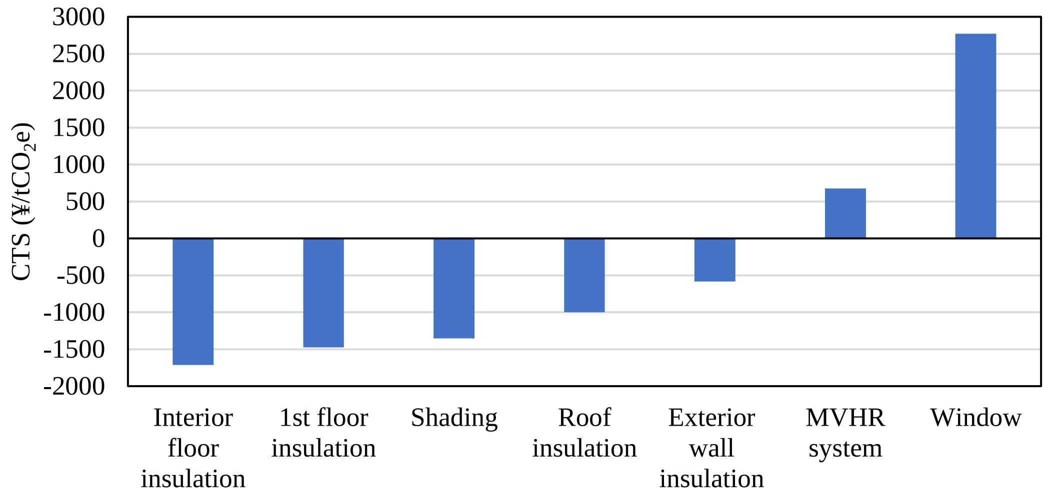


Figure 6-16: Cost each tonne of carbon saved (CTS) of the different retrofitting measures.

Based on Equation 6-4, the CTS performances of each of the single measures were identified and are show in Figure 6-16, in which the efficiency was ranked from high to low. According to the results, all of the measures in which insulation was applied to different parts of the envelope could achieve monetary savings, while the carbon emissions would be reduced at the end of the lifetime, and the measures of MVHR system and windows cost money to achieve carbon emission in this life cycle. Among those evaluated measures, the insulation for interior floor was the most efficient measure in terms of the cost to carbon reduction, while the high-performance window had the least efficiency. The measure of exterior wall insulation, which had the best cost and carbon saving, was not necessarily the measure with the best CTS result, since its efficiency of cost in terms of carbon was moderate.

When compared with the CTS results of the retrofitting plans as a whole, the CTS results of those single measures were more extreme, because the amount of carbon they saved was very small. Actually, after those analyses, it was realised that the CTS method (comparing the ratio between the saved cost and the saved carbon) was a useful way to make a comprehensive decision between various retrofitting proposals only when they all had substantial but different effects in both cost and carbon aspect. However, for the individual retrofitting measures, their effects were quite small on the carbon saving side but significant on the cost saving side over the building's lifespan, according to Table 6-16. Comparing their CTS results should not be considered a sensible way to decide the best measure among them because this ratio generates quite extreme numbers and does not reflect the actual cost and carbon savings brought by those measures. Instead, comparing their benefits on the cost side and the carbon side separately was much more sensible, and the measure of insulating the exterior wall was considered the best measure because it brought the best cost saving and the carbon saving among all the analysed measures.

6.7. Summary

This chapter assessed the life cycle carbon and cost of the retrofitting plans which were proposed in the previous chapters, in order to assist a comprehensive analysis of the performance of EnerPHit retrofitting measures from perspectives other than energy efficiency, using a case building that experienced a hot summer - cold winter climate. The life cycle analysis was carried out for a lifespan of 30 years, and the energy consumption needed for life cycle analysis was simulated with future weather files.

Analysis of the carbon payback time suggested that all the five retrofitting plans had a short payback time of just one year, because their retrofitting embodied carbon was less than the operational carbon emission of the pre-retrofit case in just one year. Throughout the life cycle, a carbon reduction of 80.5% to 83.4% relative to the carbon emission of the pre-retrofit case was expected from implementation of the proposed plans, equal to a reduction of around 4 tonnes of carbon emissions. However, it was found that the carbon result is highly dependent on the carbon factor of the energy source to operating the building. The above-mentioned results were calculated with the electricity source currently being produced in China. If UK electricity production sources had been used instead, then the carbon payback time would increase to 2 to 4 years, and the potential carbon savings in the lifespan would decrease to around 1 tonne. The carbon emissions from producing electricity are expected to be reducing in the future, thus the short payback of one year was positive news since the embodied carbon savings could be paid back quickly, and carbon savings in following operational time could be committed even if the carbon efficiency of producing electricity could be largely improved in the future.

In terms of life cycle cost, the energy price is an uncertainty that influences the result, and a binomial tree prediction model was established to predict the prices in future years. The cost payback period of implementing the proposed retrofitting plans was much longer than that of carbon, between 20 to 24 years, and at the end-of-life cycle, about 9% to 18% of the cost could be saved compared with the pre-retrofit case, which were about 195.3¥/m^2 to 390.6¥/m^2 saved.

Among the five retrofitting plans, the retrofit baseline plan had the lowest life cycle carbon, while the plan, improved 3, had the lowest life cycle cost. In order to compare the combined performance of the plans in both aspects of carbon and cost, their costs for saving each tonne of carbon (CTS) were identified as a performance indicator. Results suggested the plan, improved 3, was that which had the highest benefit for saving each tonne of carbon, where a cost of ¥ -96.78 was required. This actually suggested that this monetary saving could be achieved whilst saving on carbon use. The other four plans could also achieve monetary savings while carbon was saved, but with lower efficiencies. Thus, it could be concluded that because the proposed EnerPHit retrofitting plans could achieve much lower energy consumption in the operational stage, the initial retrofitting investment in cost and carbon could be recovered and benefit could be achieved in both aspects, though benefit in carbon reduction was more substantial. The cost of each tonne of carbon saved when the retrofitting measures were adopted individually was also identified and, overall, the application of insulation measures to the opaque envelope has better benefits compared to the use of the MVHR system and windows. Moreover, it was found that the CTS method was a very helpful way to figure out the efficiency difference in terms of both the cost and carbon saving for the retrofitting plans that have been proposed in this research. However, it was not considered suitable for the single retrofitting measures because it did not reflect the actual cost and carbon saving ability of the single measure.

In addition, it should be kept in mind that CTS is an indicator for efficiency comparison and does not mean that additional monetary investment can actually be exchanged for more carbon reductions.

Chapter 7. Conclusion

7.1. Overview

The intent of this research was to explore whether the retrofitting method that follows the Passivhaus EnerPHit concept is a feasible way to significantly improve building energy performance for existing suburban dwellings in the hot summer - cold winter climate region of China. This target was achieved through a comprehensive analysis encompassing energy consumption, indoor thermal comfort, carbon emissions and cost recovery based on a case study in Hunan. This chapter concludes this research by summarising the research content, outlining the main findings and limitations, and finally making suggestions for future studies.

7.2. Research summary

It has been mentioned previously that the existing dwellings within the hot summer - cold winter climate region were mostly uninsulated and built with basic materials like concrete and bricks. Their poor thermal performance has led to increasingly higher energy consumption since active heating and cooling have been used much more frequently following an increasing demand for indoor thermal comfort. In the past 20 years, there has been a shift in focus regarding energy consumption and carbon emissions in China from the north cold climates of the country to the south hot climates. The average annual growth rate of building energy consumption in the hot summer - cold winter climate region was 10.32% in recent years, which was the highest among all regions in China (CABEE, 2020). The rising trend of building energy consumption has increased the urgency of building energy retrofitting under this climate region. Retrofit under this climate region, with the aim of significantly decreasing building energy consumption, is a challenge for China in the near future, and this underlines the importance of this research, which explores the effect of a method with high energy saving potential, the Passivhaus EnerPHit retrofitting standard, for application to existing dwellings under China's hot summer - cold winter climate.

This research was established with the aim of evaluating the potential energy savings of retrofitting towards the Passivhaus EnerPHit standard by using the Hunan case building. As the research progressed, the aim was expanded to evaluating the performance of the Passivhaus retrofitting standard from a more comprehensive inspective, which involved thermal comfort, carbon emissions and cost benefits. For achieving the research aim, four main research questions were raised and then the research objectives were determined. The research process can be grouped into four stages, which follow the main research objectives.

Firstly, the hygrothermal data of a selected suburban residential building in Hunan province was monitored, and a baseline model using DesignBuilder was created and calibrated. Then, the retrofitting measures that followed the Passivhaus concept were applied and analysed based on this baseline model, culminating in a retrofitting plan proposal that successfully achieved the EnerPHit energy criteria. In the third stage, the proposed retrofitting plan was improved in terms of achieving the EnerPHit energy performance whilst, at the same time, reducing the amount of material used in the retrofit process. Next, the thermal comfort of the final retrofitted case was analysed. Finally, the carbon and cost performance of the proposed retrofitting plans were analysed through a detailed life cycle carbon and cost analysis. Based on the research findings from each of those stages, the research questions laid out in Chapter One can now be answered.

7.3. Main research findings

This section refers back to the main research questions proposed initially in Chapter One, and the main findings from this research will be summarised and highlighted by answering each of the research questions.

1. ***What are the retrofitting measures that enable the case building to meet the criteria of this standard?***

The answer to this question was addressed by the first and second stage of this research, in which a baseline model for the Hunan case building was created and calibrated to reliably evaluate the performance of the Passivhaus retrofitting measures, and ultimately propose a retrofitting plan.

- In research stage one, the baseline model of the case building was calibrated to set up a reliable pre-retrofit baseline model for the following retrofitting analyse. The energy performance of the existing pre-retrofit building was simulated based on this calibrated model, which suggested a high annual energy consumption of 150.6 kWh/m^2a in heating and 42.0 kWh/m^2a in cooling. This energy consumption composition suggested that the heating was dominant for existing dwellings under this climate type, which is in line with MOHURD predicted results that the heating and cooling loads were 200 million kW and 80 million kW respectively for achieving a relative comfort indoor condition for all the existing dwellings under this climate region (MOHURD, 2007).
- The indoor thermal comfort of the existing case building was evaluated based on the adaptive thermal model (ATC) and the on-site recorded thermal data.. The results showed that only 13% (49 days) of the time in a year were within the class Ⅰ comfort range (90% satisfied), and 40% (145 days) were within

the class Ⅱ comfort range (75% satisfied). This illustrates that active heating and cooling are necessary for more than half of the year in this climate region.

- In research stage two, the retrofitting measures that may enable the case building to achieve the EnerPHit standard were analysed in DesignBuilder based on the baseline model. The results demonstrated that this standard was successfully achieved with the baseline retrofit plan which was proposed in this research stage, this plan involved five main strategies.
- The first strategy was the insulation of the whole envelope, including a 250mm layer of Rockwool insulation material was applied to the entire opaque enclosure and also the interior floors; the windows were replaced by triple glazed LoE windows, and the doors were also changed to insulated doors. These measures significantly improved the envelope's thermal performance, and 94% of the annual heat loss from the envelope was avoided. However, it was found that those measures were not equally efficient. All of those measures worked better in decreasing heating demand than cooling demand, in which the exterior wall insulation worked the best for reducing heating demand. The high-performance windows worked significantly well to reduce both heating and cooling demand, even as they increased the solar gain during the summer months. The insulated doors were ineffective in terms of improving the energy performance since they face a semi-exposed space rather than an outdoor space in this case.
- The second strategy was improving the airtightness level from the baseline of 3 ach to an excellent level of 0.6 ach, which saved 73% of the heat loss due to envelope infiltration and, accordingly, largely improved the energy performance.

- The third strategy was adopting a mechanical ventilation system with a heat recovery function (MVHR). It was found that latent heat recovery was necessary for the studied climate type since the humidity level is high. This function increased the condensation, therefore improving the efficiency of cool temperature recovery. Moreover, it was also found that the amount of fresh air supplied by the MVHR system affected both the heating and cooling demand. As a result, an MVHR system with 85% sensible heat and 80% latent heat recovery efficiency, which supplies minimum fresh air per person (36 m^3/h), was selected for the case building.
- The fourth strategy involved the heating system, and it was found that the indoor temperature was unstable and could be as low as 8.5 ºC when the heating system was off, and so heating is indispensable for maintaining the indoor thermal comfort for the studied climate even when the envelope was sufficiently insulated. To further decrease the heating demand, the coefficient of performance (CoP) of the heating system was increased slightly to 1.2.
- The fifth strategy was about the passive cooling methods. Based on an analysis of the solar gain received by the exterior windows and different shading methods, it was found that exterior window blind shading slats with a low solar reflectivity of 0.2 slat worked the most efficiently for the case building. Natural ventilation was found to be a helpful but less efficient passive method for decreasing the cooling demand because it was only for about 20% of the year, mostly during transitional seasons, that the outdoor temperatures were suitable for natural ventilation.

2. ***How much energy saving could be achieved by implementing EnerPHit standard compared with the existing situation?***

This question could be answered with the findings from the research stage two, Chapter 4, of this research.

- The energy performance of the pre-retrofit baseline model was 150.6 kWh/m^{2}a and 42.0 kWh/m^{2}a for heating and cooling respectively, which decreased to 14.9 kWh/m^{2}a and 11.5 kWh/m^{2}a respectively in the retrofitted model in research stage two, giving 90.1% and 72.6% energy savings in heating and cooling energy respectively.
- The energy savings from each retrofitting measure were assessed. In summary, the retrofitting strategy involving insulating the envelope contributed 48% energy savings in heating and 30% in cooling. The second strategy, related to airtightness levels, attained 40.6% and 15.7% energy savings in heating and cooling respectively. The third strategy, involving the use of a of MVHR system, increased the heating energy by 0.3% and decreased the cooling energy by 13.3%, where the heating energy increased because natural ventilation was adjusted by the MVHR system, which supplied a healthier indoor air environment. The fourth strategy, of the heating system, contributed a 1.9% heating energy saving. Finally, the fifth strategy, about passive cooling methods, contributed 13.5% cooling energy savings. The percentage of energy saving from those measures may change if their order of application is changed, but a total cumulative heating energy saving of 90.1% and cooling energy saving of 72.6% should be achieved after they are all applied to the baseline model.

3. ***Is it possible to decrease the amount of retrofitting material inputs while still achieving the EnerPHit standard energy efficiency?***

Following the retrofitted energy results in research stage two, the possibility of reducing the retrofitting material inputs, whilst still achieving the EnerPHit standard of energy efficiency, was evaluated in research stage three, Chapter 5, of the thesis, and the findings indicated that the amounts of retrofitting materials could be reduced.

- The findings from the parametric analyses illustrated that insulating all the opaque components had a much stronger effect on heating energy saving than cooling energy saving. The amount of insulation material required to meet the EnerPHit heating criteria was reasonably sufficient for the cooling criteria to be achieved as well, while a thicker insulation layer did not seem to increase the cooling energy.
- For heating energy savings, the exterior wall was the most significant opaque component that should be appropriately insulated, followed by the roof and first floor (the bottom enclosure in this case); and the roof was the most important component that influenced the cooling energy. The insulation to interior floors was found not to effect either heating or cooling energy, so it is unnecessary to insulate them.
- The window's thermal performance was also found to be more significant for heating energy saving than cooling, as when the U-value was increased to 1.76 W/m^2K, a relatively poor level for triple glazed windows, the EnerPHit heating criteria were not met. However, the cooling criteria were met, even when a double glazed window with a U-value of 2.55 W/m^2K was applied.

- The airtightness performance had a strong influence on heating demand, and when the performance was worse than 0.8 ach, the heating criteria were not met.
- The high thermal performance for both opaque and transparent envelope components and an extremely good airtightness performance, were mainly necessary for the studied climate to achieve the very low heating demand. A lower level of thermal performance would be enough if it was to achieve the EnerPHit cooling criteria only.
- The improved retrofitting plans under the four scenarios had all achieved the EnerPHit standard, and compared with the baseline retrofitting plan, a reduction in insulation material of between 18% and 58% was achieved. Though the energy performance of the four improved retrofit plans was higher, significant reductions of about 87% for heating energy and 70% for cooling energy were still achieved when compared with the pre-retrofit case – about 20 kWh/m^{2}a for heating demand and 12 kWh/m^{2}a for cooling demand.
- From the thermal comfort evaluation of the retrofitted case, a significant thermal comfort improvement when compared with the pre-retrofit case was observed, as the monthly mean indoor temperature changed between 18.2 ºC and 26.1 ºC in the former case, and between 6.6 ºC and 32.3 ºC in the latter case. However, the predicted mean vote (PMV) model suggested that a cold feeling was experienced in the retrofitted case in heating season since the PMV level was lower than -2, and the rest time of the year were considered as comfortable. Similarly, overcooling in winter was also evaluated based on the Passivhaus comfort requirement, as 33.2% of the hours in a year was lower

than 20 ºC. According to Passivhaus requirement, there was also overheating in summer because the temperature exceeded 25 ºC for 28.1% of the hours.

4. ***Is the proposed retrofitting plan still profitable in terms of environmental impact and the monetary investment, compared with the pre-retrofit situation, when a long building lifespan is considered?***

The thesis drew the answer to this question from the life cycle studies in research stage four, Chapter six. The carbon and cost performances when the previously proposed retrofitting plans were applied to the case building were compared with its pre-retrofit condition for a lifespan of 30 years. The results indicated that both the carbon emissions and cost investment for the retrofitting plans could be paid back within the building's life, though the payback period for cost was much more extended than the carbon emissions.

- A significant difference in embodied carbon was found between the five retrofitting plans, which all enabled the case building to achieve the EnerPHit energy criteria. The case of the retrofit plan in research stage two (the baseline retrofit plan) had a high embodied carbon value of 99.33 $kgCO_2e/m^2$, because the required amount of Rockwool insulation was the highest in this plan, and the embodied carbon value of the other four improved retrofitting plans in the research stage three ranged between 56.76 $kgCO_2e/m^2$ and 86.27 $kgCO_2e/m^2$.
- The initial cost of the five retrofitting plans were also different, between 1340.5 ¥/m^2 and 1538 ¥/m^2. This difference was mostly caused by the type of windows used, and the amount of insulation material applied.
- The electricity price in future years was an uncertainty in the calculation process of operational cost impact, and it was estimated by a binomial tree

prediction analysis based on data for past prices. A slightly upward trend was found for the local electricity price.

- It was found that the carbon impact for the operational stage accounted for the most weight in all retrofitted cases, for which the percentages were between 88.1% and 93.9%. On the cost side, however, the initial cost was most significant for the retrofitted cases, as the proportion was between 75% and 80% of the life cycle costs.
- At the end of the assessed building lifespan, the amount of carbon emissions reductions from the five retrofitted cases was similar, all about 4 tCO2e/m^2, which should be considered a significant benefit as this was about 80.5% to 83.4% reductions from the pre-retrofit case. However, the cost-benefit from the retrofitting was less obvious, as only 9% to 18% of the life cycle cost could be saved in the retrofitted cases compared with the pre-retrofit case, in which in net present monetary value was between 195.3 ¥/m^2 and 390.6¥/m^2. The difference in carbon and cost benefits could also be seen in the payback periods, which was only 1 year for carbon and 20-24 years for cost.
- From the analyses of the indicator, the cost of each tonne of carbon saved (CTS), it was found that all of the retrofitting plans were able to give cost and carbon savings within the same amount of time, but the plan under scenario three, which had a CTS result of -96.78 ¥/tCO_2e, was the most efficient among the five plans, as this plan give the highest cost-saving while saving each tonne of carbon.
- However, CTS was not found as a sensible indicator to evaluate the individual retrofitting measures. Based on the separate analysis of cost and carbon saving

brought by each of the measures, insulating the exterior wall was found the most efficient one.

To conclude this research, Figure 7-1 summarises the energy, carbon and cost performance within a 30-years building lifespan of the retrofitting plans proposed for the Hunan case-building under the hot summer - cold winter climate.

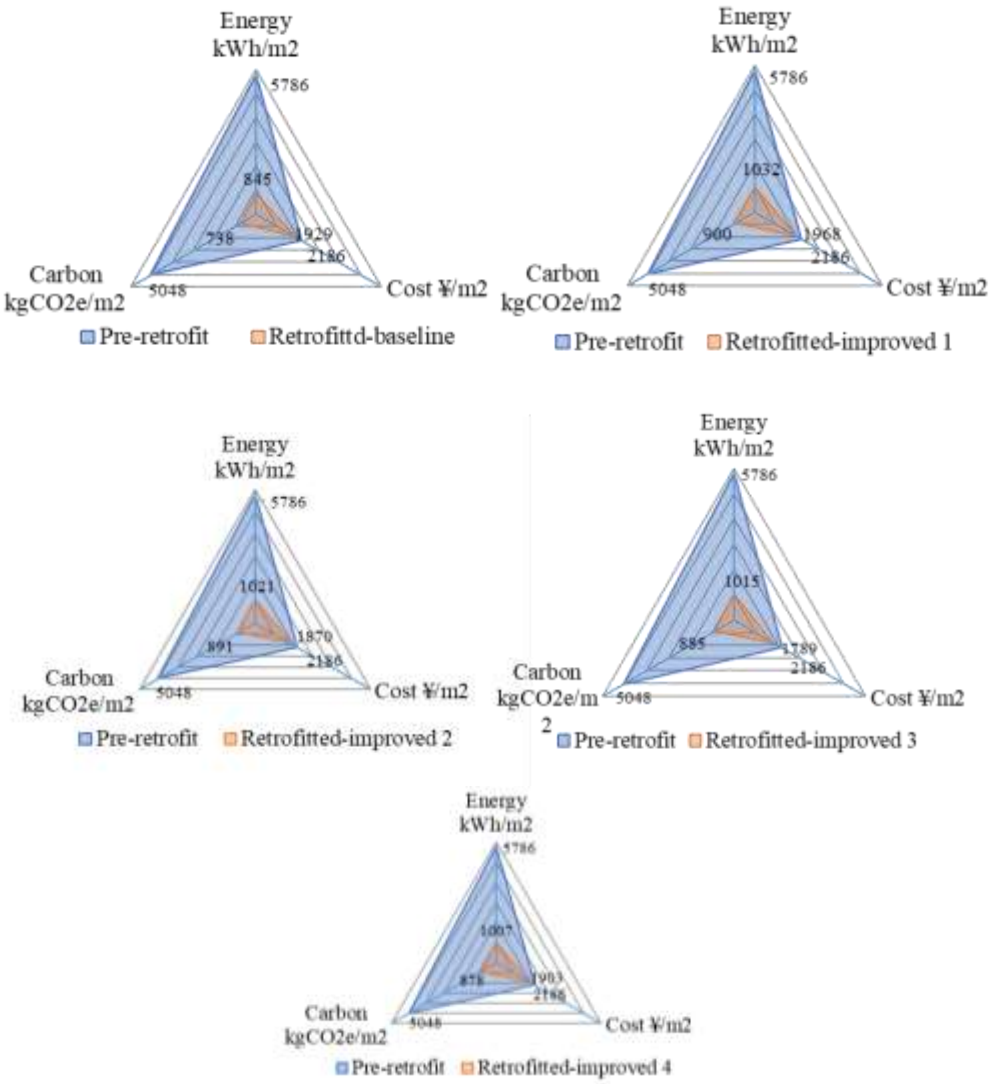


Figure 7-1: Retrofitted performance in terms of life cycle energy, carbon and cost.

The primary energy of the retrofitting measures was not included in this life cycle energy analysis, as the environmental impact from this, which was included in the life cycle carbon analysis, should be considered more significantly for retrofitting projects. The benefits that those Passivhaus standard retrofitting plans could contribute were slightly different from each other, but they all reflected a dramatic energy saving and carbon reduction effect compared with the pre-retrofit case, although the benefit in cost-savings was much weaker.

There are Chinese versions of Passivhaus standards or related similar ultra-low energy building regulations that have been or are going to be realised in coming years based on different climate types in China. However, there are very few government guidelines or reports to demonstrate how Passivhaus measures work in practice. This is important considering that the Passivhaus standard is still a relatively new concept in China and has not been widely introduced to the industry as a whole. This research supported a case study under the hot summer – cold winter climate region that demonstrated the Passivhaus effects in depth, from the most important aspects of energy saving, carbon reduction, cost saving, as well as thermal comfort, which all should be considered with great significance in future buildings. Moreover, this case study also clearly showed the sensitivity of the retrofitting measures to the building energy consumption and offered various retrofitting solutions in which different scenarios were considered. Therefore, the research results from this case study should be a valuable example that the government may consider to include in their guidelines for promoting the Passivhaus development in China.

7.4. Limitations of the research

This research explores the performance of Passivhaus retrofitting in the hot summer - cold winter climate region in China. The findings provided by this research were limited within the research scope, in which the analyses were focused on the performance indicators of energy, carbon, cost and comfort of the Hunan case study. More specific limitations existed in each of the research stages. During the first stage, the baseline model was calibrated on the basis that the simulation weather file was edited to fit the actual outdoor weather condition, but the data used to edit the weather file were limited to the recorded outdoor dry bulb temperature and relative humidity, and other essential weather figures, such as wet bulb temperature, solar radiation and wind were estimated. Moreover, interior heat source related inputs, such as human metabolism, lighting, household equipment and their operating schedules, which are essential for DesignBuilder simulations, were based on the ASHRAE guidance about typical situations in residential buildings rather than on-site investigated data. However, those inputs were kept the same in pre-retrofit and retrofitted cases in order not to affect the retrofitting measures by comparison.

In the second and third stages, the energy performance related analysis was only based on the heating and cooling energy. This was because it is particularly significant for the hot summer - cold winter climate, so this research was only focused on the savings from the Passivhaus retrofitting. However, the Passivhaus standard required the total primary energy consumption of 120 kWh/m^2a, but the results calculated based on DesignBuilder simulated consumption was beyond this requirement. Thus, measures and actions that could lower the primary energy usage from other household applications other than heating and cooling should be considered in future studies, especially those based on the post-occupied Passivhaus case study.

Two uncertainties existed in the life cycle carbon and cost assessments for the case building. Firstly, the embodied carbon data of the electricity for the operational carbon calculation in 30 years lifespan were based on the current data on energy generation. The carbon emission due to energy generation should be gradually lowered due to the increasing use of renewable sources, but the exact value is considered extremely difficult to predict. Similarly, the future price of electricity is another uncertainty. This research tried to decrease this uncertainty by adopting a binomial tree method that predicts future prices. However, according to the collected data, the electricity price in Hunan has not changed in the past 10 years because of government regulation.

7.5. Opportunities for future work

This research aimed to explore, through a detailed case study, whether the Passivhaus EnerPHit standard is a method which could bring significant energy savings for China's suburban dwellings in the hot summer - cold winter climate region, and the results were very encouraging in this case study. However, more case studies are required to evaluate the performance of Passivhaus retrofitting before it can be considered as an efficient method that can be implemented to existing large-scale dwelling retrofit programmes in the studied climate region. For this ultimate goal, a few research opportunities for future study in this field could be suggested based on the experience of this research:

- Studies based on real Passivhaus projects located in this climate region should be one of the most valuable research sources for this research topic. Build and post-occupied Passivhaus buildings should be more accessible now or in the near future because of the rapid development of the Passivhaus standard in China over the past few years. Evaluation of Passivhaus thermal and energy performance according to on-site recorded data and comparative analysis with the modelled performance should be a valuable contribution to the research.

- The Passivhaus retrofitting method is considered to have considerable energy saving potential. Combining Passivhaus retrofitting and renewable energy generation system research is a research opportunity to achieve higher energy conservation standards and lower carbon emissions for existing dwellings.
- In European studies, occupant behaviour was found to be a factor that impacts on the actual Passivhaus performance. This factor could be significant in future research for the hot summer - cold winter climate region because it has a dual effect on increasing heating and cooling energy consumption. Thus, future studies that involve Passivhaus energy simulations with on-site investigated behaviour schedules should be required.
- Life cycle performance is an essential factor when planning deep retrofitting. This study only evaluated the life cycle performance of the proposed retrofitting plan under a moderate prediction of climate change due to the time limitation. Future studies should consider the performance under different scenarios of climate conditions and analyse the changes in retrofitting measures for responding to future weather patterns.
- This research did not include the impact of the construction stage on life cycle studies. However, it is significant, especially for cost analysis, as it is part of the retrofitting investment and would change the payback result. Studies investigating the impact of this stage on the local building industry and including it in the assessment could improve the value and reliability of life cycle studies.

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Appendices

Appendix (A). List of publications

Liu, C., Mohammadpourkarbasi, H., & Sharples, S. (2021) 'Evaluating the potential energy savings of retrofitting low-rise suburban dwellings towards the Passivhaus EnerPHit standard in a hot summer/cold winter region of China'. *Energy and Buildings*, 231, p. 110555. doi: 10.1016/j.enbuild.2020.110555

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Liu, C.; Sharples, S.; Mohammadpourkarbasi, H. (2019) 'Analysing the benefits and challengings of retrofitting dwellings in Hunan, China to the Passivhaus EnerPHit standard'. In IOP Conference Series: Earth and Environmental Science Vol. 329 (pp. 012008). IOP Publishing. doi:10.1088/1755-1315/329/1/012008

Appendix (B). Prediction of future electricity prices by binomial tree method