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Sustainable Design Optimization of Rural Houses in North China

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SUSTAINABLE DESIGN OPTIMIZATION OF RURAL HOUSES IN NORTH CHINA

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of

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In Partial Fulfillment of the

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of

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To my parents, for enlightening my life.

To my wife, for her endless love and support.

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ABSTRACT

Li, Mingliang. M.S., Purdue University, August 2011. Sustainable Design Optimization of Rural Houses in North China. Major Professor: Kirk Alter.

With the rapid economic development of China, the living standards in rural areas have been experiencing improvement over the past two decades. One important aspect of the improved living standards is housing, which has been transformed from traditional adobe or stone structures into modern brick and concrete ones. In the meantime, active heating and cooling systems are gradually being incorporated and residents are requiring more comfortable indoor air temperatures during cold winters and hot summers. However, most rural houses have no insulation in their exterior walls and roofs. The question is whether or not it is economically viable to build houses with insulated exterior walls and roofs, and to what extent should they be insulated.

In order to answer these questions, the author has created one base hypothetical case and two evolutionary hypothetical cases. The base case is assumed to represent typical rural houses in the studied region of northern rural China, with its heating set point temperature at 13 °C (55 °F) and cooling set point temperature at 29 °C (84 °F). The two revolutionary hypothetical cases, reflecting the improving living standards in rural areas in the future, are the same with the base case, except that the set point temperatures are different. The heating set point temperature is 16 °C (61 °F) for evolutionary case 1 and 18 °C (64 °F) for evolutionary case 2. The cooling set point temperature is 26 °C (79 °F) for evolutionary case 1 and 23 °C (73 °F) for evolutionary case 2. The life cycle

costs of each case with different insulation levels are calculated based on the initial cost and energy consumption data from EnergyPlus energy modeling software.

For all three cases, it was cost effective to insulate exterior walls and roofs. The optimal insulation scenario is 50 mm (2 inches) Expanded Polystyrene (EPS) wall and 25 mm (1 inch) Extruded Polystyrene (XPS) roof for the base case. The best insulation scenarios for evolutionary case 1 and case 2 is 100 mm (3.9 inches) EPS wall and 75 mm (3 inches) XPS roof and 100 mm (3.9 inches) EPS wall and 100 mm (3.9 inches) XPS roof respectively. It has also been found that the determinants on the optimal insulation scenarios are the heating and cooling set point temperatures, energy prices, lifetimes of houses and selected discount rates.

CHAPTER 1. INTRODUCTION

This chapter introduces the research with the statement of problem, significance of the research, and the purpose of the research. In addition, the assumptions, limitations, and delimitations of the problem are stated to define the basis and scope of the study.

1.1. Statement of Problem

With the rapid development of China's economy, the country's rural areas are also experiencing dramatic changes. In the meantime, the construction of new houses has been at a high level since the 1990s. In 2008, the floor space of newly built houses in rural China was 714 million m^2 (7.69 billion ft^2) (*Figure 1.1*). China's building sector accounted for 23% of its energy consumption in 2005 and was projected to rise to one third by 2010 (Liang, Li, Wu, & Yao, 2007). According to Martinot (2001), the average growth rate of energy consumption in the residential sector was 16 percent from 1980 to 1994.

However, the energy efficiency of buildings, especially rural residential buildings, has not improved significantly. The low insulation level of residential buildings is one of the major reasons for the low energy efficiency. *Figure 1.2* shows the comparison of heat transfer coefficient of residential building in Beijing, Germany, and the United States. The heat transfer coefficients of outer walls and windows in Beijing is around twice that in Germany and the United States, and the heat transfer coefficient of roofs in Beijing is more than ten times that of Germany and the United States.

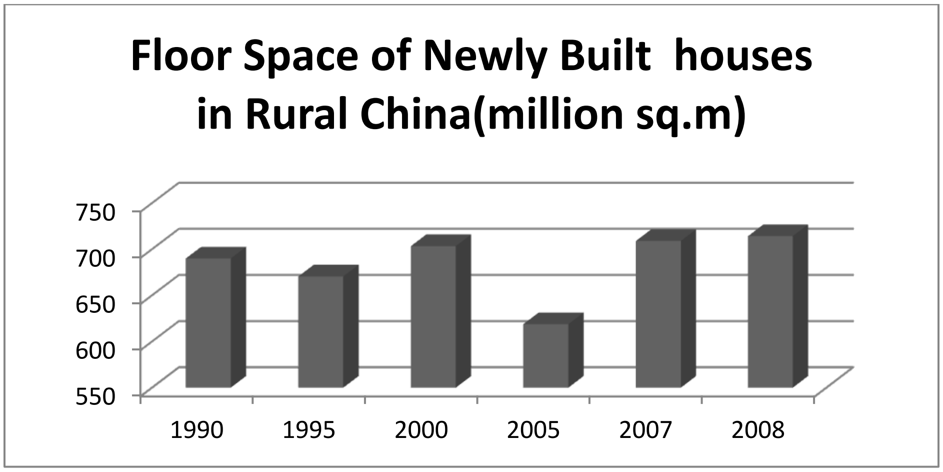

Figure 1.1 Floor Space of Newly Built Houses in Rural China (National Bureau of Statistics of China, 2010)

In rural areas in northern China, where most of the buildings are detached single houses, the insulation level of building envelopes is even lower. The typical construction type in northern rural areas is brick-concrete construction, in which walls are made of brick as both a structural and insulation material, while roofs are made of reinforced concrete slabs. From the cold to severely cold climate zones (*Figure 1.3*), there are normally three different thicknesses of exterior brick walls: 240 mm (9.4 inches), 370 mm (14.6 inches), and 490mm (16.3 inches); the heat transfer coefficient is about 2.40 W/m^{2}K (0.42 Btu/h·ft^2·°F), 1.84 W/m^{2}K (0.32 Btu/h·ft^2·°F), and 1.28 (0.23 Btu/h·ft^2·°F) W/m^{2}K respectively(Jin & Zhao, 2009).

Although the building insulation levels in rural areas are lower compared to those in urban area residential buildings, like in Beijing, the energy consumption is less than in urban areas. The residential buildings in rural areas consume about 7 KWh/m^2 (2219 Btu/ft^2) for heating, while those in northern cities consume 57 KWh/m^2 (18069 Btu/ft^2) (Cai, Wu, Zhong, & Ren, 2009). This seems to be somewhat conflicting, given that the buildings in rural areas are less insulated than those in urban areas, but consume less energy. The reason for this conflict is that the low energy consumption in rural areas is at the expense of indoor air comfort. In heating season, the indoor air temperature in rural areas can be as low as 0 °C (32 °F) because a lot of houses do not have heating equipment. Even in those households with heating systems, the indoor air temperature is around 10 °C (50 °F) based on the author's experience. With the development of rural areas, the indoor environment comfort levels will increase, which means a significant increase in energy consumption if the building energy efficiency remains low. Thus, a solution to energy efficient, comfortable - yet affordable - rural houses becomes critical for the sustainable development of rural areas.

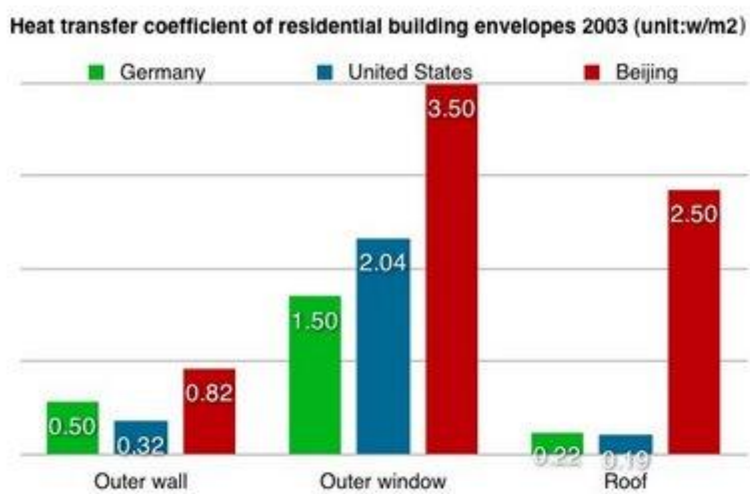

Figure 1.2 Building envelope insulation level comparison (Lewis, 2009)

The motivation for doing this research is two folds: the primary one is to study the optimal design strategies with low life cycle cost, energy consumption, and high indoor air comfort level. The other, which is the ultimate goal, is to avoid the traditional building evolution mode, which developed from low energy consumption and low comfort level buildings to high energy consumption and high comfort level, and finally, to low energy consumption and high comfort level buildings by stepping directly to low energy consumption and high comfort level building.

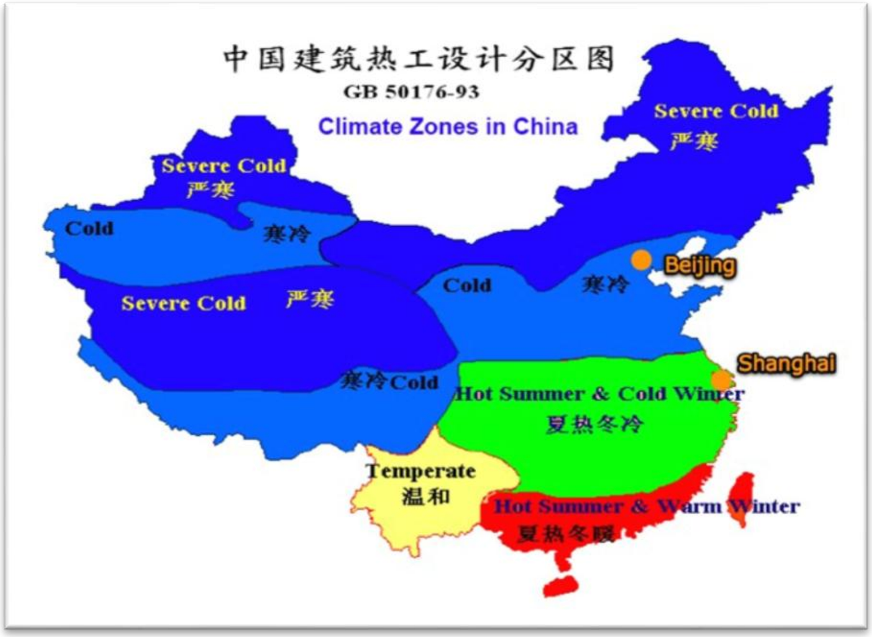

Figure 1.3 Climate zones in China

1.2. Research Questions

The research mainly focuses on one primary research question and three secondary questions.

1.2.1. Primary Research Question

- What are the optimized exterior wall and roof insulation levels for rural houses in northern China considering the life cycle cost of houses and different indoor air comfort levels?

1.2.2. Secondary Research Questions

- How should we evaluate design solutions for rural houses in northern China?
- How can we find the optimal exterior wall and roof insulation levels of rural houses in northern China?

- What factors are most critical in determining the exterior wall and roof insulation levels of rural houses in northern China?

1.3. Scope

In order to design a single detached house that will be occupied in rural northern China, the social and economic settings of rural China was briefly researched to provide a solid basis for the design. The setting includes the laws, building codes, and standards that regulate building design and construction, especially from the energy efficiency's perspective.

The optimization exterior wall and roof insulation level in the sustainable design of rural houses is the main focus of this research. The insulation scenarios of walls and roofs were selected from a range of alternatives. Energy simulation software EnergyPlus was used to model the energy consumption of the selected building design solutions.

1.4. Significance

A significant amount of research has been carried out on energy efficient buildings and a number of building envelope techniques have been developed and implemented in China. As the development of rural areas has been greatly emphasized within the past few years, research about comfortable and energy efficient houses in these areas has also increased. Universities, architectural design firms, and building materials suppliers have invented different energy efficient techniques, especially for rural houses (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2010a, 2010b). Although these techniques can improve the energy performance of rural houses, the energy efficiency is still low when compared to that in developed countries. This research aimed to find the optimal insulation levels of exterior wall and roof with low life cycle cost and high indoor air comfort levels. In addition, these strategies can be employed to find the optimal insulation levels of high-rise condominiums and commercial buildings after proper adaptation.

1.5. Definitions of Key Terms

Building envelope is an interface between the interior and exterior of the building, including walls, floors, roofs, etc. which serves as the outer shell to protect and facilitates the control of the indoor environment.

R-value is a measure of thermal resistance used in the building and construction industry. Under uniform conditions it is the ratio of the temperature difference across an insulator and the heat flux (heat transfer per unit area, $\dot{Q}_A$) through it or R = $\Delta T / \dot{Q}_A$.

U-value (or U-factor), more correctly called the overall heat transfer coefficient, describes how well a building element conducts heat and U = 1/R = $\dot{Q}_A / \Delta T$.

Passive house is a building design and construction standard that requires maintaining a comfortable indoor environment both during summer and winter without any conventional heating or cooling system (Badescu & Sicre, 2003).

1.6. Assumptions

The research is conducted and results are interpreted with the following assumptions:

- The energy consumption calculated by the energy simulation program EnergyPlus accurately reflects the actual energy consumption when an actual house is occupied by a household in rural northern China.
- The estimation of construction and installation cost based on the construction cost database accurately reflects the real cost.

- In this study, the operating cost for the rural house is the energy cost during the house's lifetime. It is assumed that the energy consumption remains the same during the studied lifetime of the house. The maintenance cost is assumed to be zero.
- The research is assuming that the decision maker is the household. The cost effectiveness assessment is from the household's point of view, instead of the policy makers such as the government and other related authorities.
- The evaluation of the house is only based on its life cycle cost and air speed and relative humidity is set the same for all cases.
- For the building envelope, only the insulation levels of exterior wall and roof were studied and manipulated; it is assumed that building facades will be designed according to the acceptable styles both culturally and aesthetically.
- The construction methods, materials, and installations employed in the design solutions of this research are common in the area within the studied climate zone.

1.7. Delimitations

The research is carried out with acknowledgment the following delimitations:

- Only the most common building shape and aspect ratio was considered, which limited the variations available.
- The embodied energy in the building materials will not be included in the life cycle cost analysis model.

1.8. Limitations

The methodology employed in the research lends itself to the following limitations:

- The research is limited to rural areas with similar climates to the one studied in northern China.
- The independent variables are not exhaustive and only reflect the tip of the iceberg with regards to different building design variations across the world.

1.9. Chapter Summary

This chapter defines the research agenda by introducing the research questions, the scope of the research, its assumptions, limitations, and delimitations. In addition, the significance of the research is addressed briefly to give an overview of its benefits.

CHAPTER 2. REVIEW OF THE LITERATURE

This chapter consists of eight sections. The first section is the introduction. The second section addresses building energy consumption in China, which includes comparisons with that of Europe and the United States. The third section reviews the design codes and standards in China. The relationship between building energy consumption and building envelop is addressed in Section 2.4. The fifth section talks about energy efficient building envelope technology and research in China. Review of building energy simulation software is provided in Section 2.6. Section 2.7 reviews the cost effectiveness assessment methods. The last section is the summary of this chapter.

2.1. Introduction

China has been undergoing rapid development in the past few decades. According to Martinot (2001), China had a two-digit economic growth rate for the past two decades, which indicates a huge energy consumption increase, as well as great impacts on the environment. With such growth, the total energy consumption also grew with an average annual rate of 3.8 percent during the period from 1980 to 2001, or from 603 million tons of standard coal equivalent to 1320 million tons (Yang, Lam, & Tsang, 2008). The building sector in China accounted for 23% of the total energy consumption in 2005 and was estimated to increase to one-third by 2010 (Liang, et al., 2007; Wu, 2003). Thus, the energy efficiency of buildings has become critical in order for China to achieve overall high energy efficiency across different sectors.

2.2. Building Energy Consumption

In the 1970s, an energy crisis hit the major industrial countries, particularly the United States, which faced a great shortage of oil. As a result, the oil prices went up quickly after the crisis in the early 1980s and have maintained a high level since 2005 (*Figure 2.1*). Since the crisis, the motivation to conduct research into alternative energy sources becomes stronger and stronger. At the same time, finding new ways to use traditional energy more efficiently has become critical to achieving sustainable development.

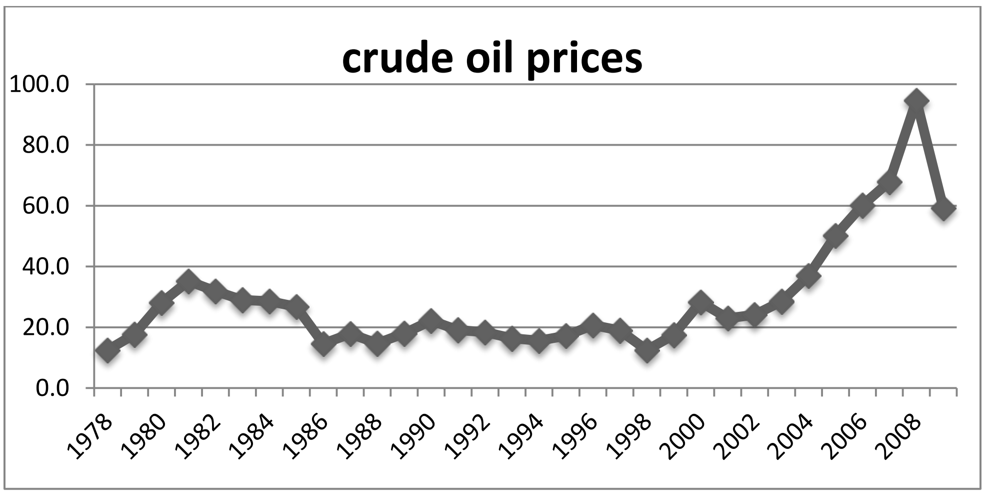

Figure 2.1 Crude oil prices from 1978 to 2009(U.S. Energy Information Adiminstration, 2010)

Building sector energy consumption is, of course, one of the targets for saving energy because this sector is one of the main energy consumers. In the US, the building sector has accounted for around 40% of total US energy consumption since the 1980s, and is projected to stay at the same level through 2030. Space heating and cooling constitutes 34.1% and 8.2% of total site energy use respectively. For the energy sources, natural gas accounted for 31% of the total primary energy, petroleum 18%, coal, 39%, renewable, 9%, and nuclear, 15% (U.S. Department of Energy, 2009)

The contribution of building sector energy consumption in China is much lower than that of the US, The building sector in China accounted for 23% of total energy consumption in 2005. However, it was estimated to increase to one third by 2010 (Wu, 2003). According to the National Bureau of Statistics of China (2010), in 2008, the primary source of energy consumption were coal, crude oil, natural gas, and hydro-power, nuclear power, and wind power, which accounted for 68.7%, 18.7%, 3.8% and 8.9%, respectively. Due to the improvement of the living conditions and standards, the energy consumption in the building sector will continue to increase over the next few decades.

However, little attention has been paid to building energy consumption in the rural parts of China where there are 720 million people or about 54.32% of the total population (National Bureau of Statistics of China, 2010). Scant literature has talked about how the buildings in rural area China consume energy. Yet, some indications of increasing energy consumption can be found indirectly. For example, the number of packaged air conditioners installed per 100 rural households grew from 0.18 in 1995 to 9.82 in 2008. As the development of rural areas continues, the number is growing fast, which will increase the energy consumption for cooling in those areas (National Bureau of Statistics of China, 2010). At present, the method for “cooling” in summer is to use electric circulating fans, which is very dominant in the rural areas.

The primary heating energy source is coal, and the cooling energy source, if any, is electricity. The primary energy consumption for a household in winter is coal for heating, with the average household consuming one ton to three tons of coal for a whole winter, costing between 120 to 360 US dollars (based on my observations in my hometown). For the electricity costs, the average national annual consumption for a rural household is 962 KWH (3.28 MBtu), which costs about 71 US dollars (National Bureau of Statistics of China, 2010). With this level of energy consumption, most households cannot maintain a comfortable indoor air temperature in hot summers and cold winters. Although the energy consumption is extremely low compared to that of developed countries, it is crucial to keep it at a low level while increasing the indoor comfort level in the buildings.

2.3. Building Energy Efficiency Laws and Standards in China

China has been improving the energy efficiency of its buildings for the past few decades. In 1998, China enacted the Law of the People's Republic of China on Energy Conservation, which states that energy related laws and regulations conform to the design and construction process (Wang, Bai, Yu, Zhang, & Zhu, 2004). The law aims to improve overall energy efficiency throughout different industries and sectors, which can ultimately protect the environment. This laid the legislation foundation for the energy efficiency in the building sector. Also, in the series of Tenth Five-year Plan and Eleventh Five-year Plan, the government also stated its aim to reduce energy consumption per unit of gross domestic product (GDP) (Yao, Li, & Steemers, 2005).

In addition to the law, there are a series of building energy conservation standards and regulations that are enforced at different levels of authority. There are two main categories of standards related to building energy conservation. One is the standard values concerning the HVAC system (Heating, Ventilating, and Air-Conditioning), which includes heating and cooling temperature set points, controlled relative humidity, air change rate, etc. The other is regarding the building envelope design standards, which set boundary values, for example, the maximum window to wall ratios in different climate regions, the minimum thermal resistance of walls, and windows, etc. (Wang, et al., 2004). Under these two categories, there are several standards for each. Those standards can also be categorized by the level of their application. Firstly, the standards are divided into two sectors: civil building (i.e., commercial and residential buildings) and industrial building. Standards for Civil Building Heating Design and Standards for Civil Building Lighting Design are the two basic national standards. In the residential design standards, they were also categorized by different climate regions. Under each of them, there are more specific standards. *Figure 2.2* illustrates the energy policy/standards structure in China (Wu, 2003). In addition, Yao et al. (2005) summarized the major Chinese Standards related to energy efficiency in buildings (Table 2.1).

Although the structure of the energy policy appears to be systematic, there are several problems with the standards and their enforcement. According to a survey by the Ministry of Construction, only 6.5% of newly constructed buildings which were designed according to the Design Standards for Energy Efficiency of Civil Buildings (heating residential buildings) legislation (JGJ26–95) in northern urban areas by 2001 (Wang, et al., 2004).). For example, in Design Standards for Energy Efficiency of Civil Buildings (heating residential buildings) legislation (JGJ26–95), the maximum energy transfer coefficient is 0.90 W/m^2K (0.16 $Btu/h{\cdot}ft^2{\cdot}°F$) for exterior walls in Beijing. Those energy efficient standards, even if the buildings meet the stated level of efficiency, are still lower than the energy efficiency standards set by developed countries.

Table 2.1*China's main building energy standards (Yao et al., 2005)*

Year	Title	Code
1986	Code of thermal design for residential buildings	JGJ24-86
1986	Energy conservation design code for heating residential buildings	JGJ26-86
1987	Design code for heating, ventilation and air conditioning	GBJ19-87
1993	Code of thermal design for residential buildings	GB50176-93
1993	Energy conservation design standard for the building envelope and air conditioning for tourist hotels	GB50189-93
1995	Energy conservation design standard for heating new residential buildings	JGJ26-95
2001	Design standard for energy efficiency of residential buildings in hot summer and cold winter	JGJ134-2001 J116-2001
2001	Technical specification for energy conservation renovation of existing heating residential buildings	JGJ 129-2000

Another concern is about the coverage of the standards. Generally speaking, they do not cover construction in rural areas which is the home to 54% of the total Chinese population. In rural areas, there are generally no authorities to enforce the application of the standards. Clearly, overall building energy efficiency in China still has a long way to go.

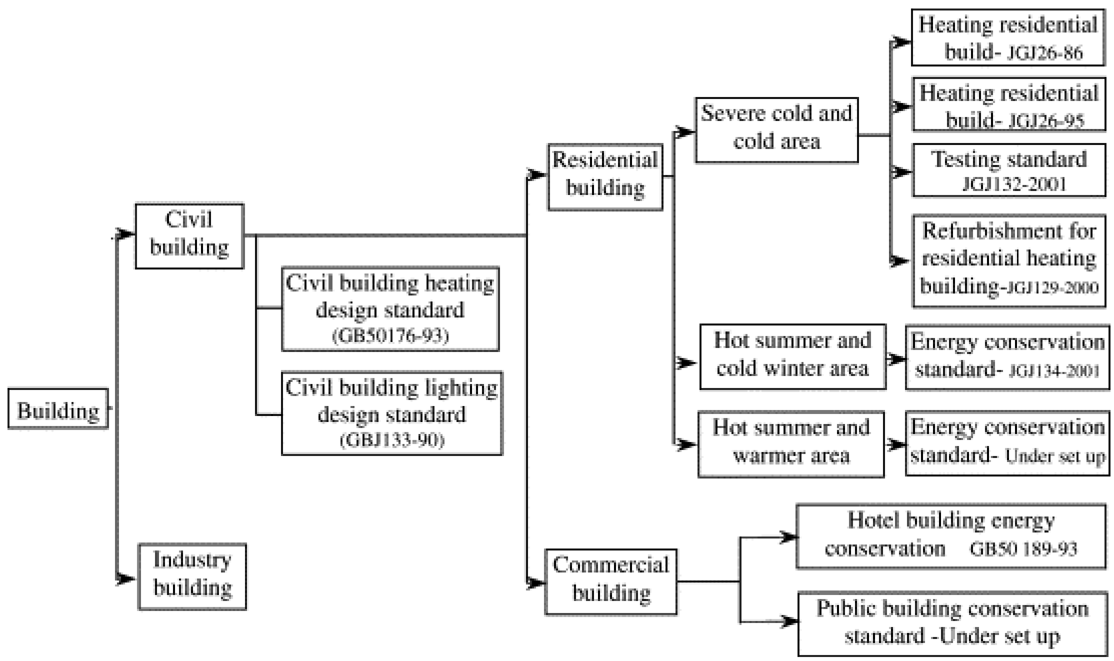

Figure 2.2 Energy policy structure in the built environment (Wu, 2003)

2.4. Building Envelope and Energy Consumption

As defined in Section 1.5, one of the functions of building envelope is to control and maintain the indoor environment with heating, ventilation and air conditioning (HVAC) equipment if any. In this process, the HVAC equipment consumes energy. The performance of building envelope, however, has a direct effect on the energy consumption of the HVAC system. The following literature demonstrates the importance of building envelope in affecting building energy consumption:

Yu, Yang and Tian (2008) conducted a study on the best design strategies of residential buildings in hot summer and cold winter climate zones in China. They analyzed different factors of building envelopes, such as exterior wall insulation level, exterior wall solar radiation absorbance, etc. By simulating the energy consumptions of different energy saving strategies in eQUEST software, it concluded that employing building envelope energy saving design, the annual electricity consumption can be reduced by 25.92%, with cooling decreased by 21.08% and heating by 34.77% respectively. It also showed a reduction of heating electricity consumption of 30.31% when insulated by a layer of 100mm (3.9 inches) extrusion polystyrene (EPS) in the interior of the wall.

Another similar study was conducted to evaluate the influence on annual cooling energy consumption of the position of insulation layer in exterior wall in Hong Kong (Bojic, Yik, & Sat, 2001). The annual cooling energy consumption was reduced by 6.8% when a 50 mm (2 inches) EPS insulation layer was placed either inside or outside the wall. When increasing the thickness of insulation from 50 mm (2 inches) to 150 mm (5.9 inches), the reduction on annual cooling energy consumption is not more than 1%. Asan (1998) found that the exterior wall insulation thickness and position has a significant impact on the time lag and decrement factor which affects the energy consumption of the building. Cheung, Fuller, & Luther (2005) observed a saving of 31.4% of annual cooling energy and 36.6% peak cooling load compared to the base case by using energy efficient building envelope design.

However, little literature can be found regarding the energy efficiency design of envelopes of rural houses in northern China. The extensive literature regarding the building envelope design of high rise residential and commercial building design is useful in improving the building envelope performance of rural houses in northern China. However, the rural houses in northern China have their own characteristics compared to the high rise residential and commercial buildings.

First, houses in northern China are usually one or two story and detached from each other. They have more exterior wall per unit interior space. This makes the indoor environment more suspected to the change of exterior weather conditions. For single detached houses, the heat loss through exterior walls in winter and heat loss in summer is faster compared to multi-unit high rise building. In addition, the insulation level of roof in single detached houses is more important. The heat loss/gain through roof in single detached houses affect the whole building, while for high rise buildings, it only affects the top floor.

Second, their insulation levels are low compared to high rise buildings in urban areas in China. A certain level of insulation, 50 mm (2 inches) expanded polystyrene (EPS), for instance, has been installed in the building envelope in the high rise buildings. The houses in rural areas, however, have barely been insulated. People in rural areas in northern China are still building their houses without any insulation. The space for improving the performance of the building envelopes in rural areas is huge.

Therefore, it is inappropriate to apply the energy efficiency strategies drawn from the previous studies on high rise buildings in rural areas directly to the houses in rural areas. A study on the building envelope of rural houses is necessary to provide the best strategies for rural houses in northern China.

2.5. Energy Efficiency Building Envelope Techniques in China

A form of traditional Chinese buildings was constructed by using the dirt blocks or rock blocks as the walls; while the roof was supported by rafters. On these rafters, there is a layer of batt that is made from reed plant. It is then covered by a layer of mud with tiles on it to shed water away. According to Saleh(1990), due to the low thermal conductivity and high thermal capacity of mud, it can flat the fluctuation of temperature during the day and night, thus providing a relative steady thermal indoor environment.

With the development of concrete and brick, traditional adobe and stone construction has gradually faded away. The predominant construction materials are now brick and concrete in rural areas. And the majority rural houses do not have any additional insulation. This makes the building envelope very inefficient.

In order to solve this problem, there are a lot of initiatives being implemented on designing wall systems and roof systems with both high structural and thermal performance. The Ministry of Housing and Urban-Rural Development of the People's Republic of China (MHURD) (2010) has issued two indices regarding sustainable building techniques; one is the Index for Sustainable Building Construction Techniques in Rural and Urban Areas; the other is the Index of Energy Efficiency Retrofitting of Existing Buildings.

Zhu and Lin (2004) researched the best mode for the sustainable development of housing design and construction in China. They recommended some valuable strategies for designing a building informed by the philosophy of passive architecture. They used simulation software to model the climate environment of the buildings being designed, which include the wind environment, thermal environment, solar isolation environment, etc.

Currently, the predominant insulation materials in China are expanded polystyrene (EPS) and extruded polystyrene (XPS). Since the cellular structure of XPS is closed, it does not absorb water. Therefore it is commonly used in roof insulation. EPS is commonly used in exterior wall insulation because of its widely recognized stability in keeping its dimensions and its ability to endure various weather conditions.

2.6. Building Energy Simulation Software

The best way to know the energy consumption of buildings is to get the energy bills from the utility companies. However, for a building in its design phase, this is impossible. Its energy consumption has to be estimated. There are two ways to estimate the energy consumption: one is to use energy consumption data of similar buildings in the similar areas and the other is to use energy simulation software. Using energy simulation is more advantageous over using energy consumption data in this research. Energy simulation is more adaptive and flexible. The buildings simulated can be exactly the same as designed, which cannot be realized when estimating by energy consumption data. Energy simulation software can easily change or add energy efficiency strategies to compare with the base model. In addition, the heating and cooling energy consumption of existing rural houses in China is not available, which makes it impossible to estimate the energy consumption based on previous data.

At present, various kinds of whole building energy simulation software are in use. There are also many research papers which provide comparisons of the most commonly used simulation software. Crawley, Hand, Griffith, and Kummert (2008) compared 20 major building energy simulation tools based on different functions. Energyplus is one of the best tools with more accurate space temperature prediction capability. Shaurette (2010) searched the simulation tools based on their user interface, complexity to use, cost and validity, etc. It was found that Energy-10 and eQUEST are two tools which have most desired attributes. Energyplus is one of the best options except that it needs significant training. However, the author is proficient in using Energyplus, which makes it one of the best choices. According to Crawley, Lawrie et al. (2001), “EnergyPlus includes a number of innovative simulation features such as variable time steps, user-configurable modular systems that are integrated with a heat and mass balance-based zone simulation”. The houses in rural areas in northern China have a lot of thermal mass in the roof, and interior and exterior walls. The advantage of Energyplus in simulating thermal mass fits the need of this research very well.

2.7. Cost Effectiveness Assessment

Before making a cost effective assessment for energy efficient design strategies, the first task is to figure out who the decision maker is (Proost & Van Regemorter, 2000). If the decision maker is a household, the assessment will only be based on the financial cost and benefits that is directly related to the household, which includes the initial added construction cost, the interest if financed, and the energy cost savings during the life time of the building (Verbeeck, 2007) . If the decision maker is the policy makers, such as the local governments, the view is different. Policies, building codes and stimulation programs relating to building energy efficiency, will not only be assessed by their direct financial impacts, but also from the social and environmental aspects, such as unemployment, tax income and environmental issues (Verbeeck, 2007).

This research, as stated in the assumption, stands from the household's point of view. At present, in rural areas, building codes are not applied to houses in rural areas in China. There are no minimum and maximum limits as to how to build the building envelope. Therefore, the assessment will focus on the cost and saving of energy efficient design strategies on building envelopes. The next step is to determine which cost effective assessment method should be used to evaluate energy efficient design strategies for building envelope of rural houses in northern China.

One of the most commonly used assessment method is simple payback time. Although not considering money's time value, it is very intuitive and very suitable for assessing projects with short lifetime, usually less than 5 years (Verbeeck, 2007). For example, one company will rent an office for 5 years and wants to evaluate the cost effectiveness of several energy efficient measures;

simple payback method can be a good option. For long lifetime projects, it is not a very suitable criterion. Besides, it can be a dilemma when the simple payback time of two projects is the same. The performance of the projects after the payback cannot be assessed (Martinaitis, Rogoža. & Bikmanienė, 2003). Projects with shorter payback time may perform worse afterwards.

In this research, the houses are assumed to have a lifetime of 30 years which is typical based on the author's observation. In addition, from the author's experience, the owners of houses in rural areas in northern China seldom change during the lifetime of the houses. It is inappropriate to just look at the first few years of the houses to assess different energy efficient design strategies. An overall analysis of the performance of the design strategies over their life time is highly desired in this situation.

According to the definition by U.S. National Institute of Standards and Technology (NIST) (1996):

> Life cycle cost analysis (LCCA) is an economic method of project evaluation in which all costs arising from owning, operating, maintaining, and ultimately disposing of a project are considered to be potentially important to that decision. LCCA is particularly suitable for the evaluation of building design alternatives that satisfy a required level performance (including occupant comfort, safety, adherence to building codes and engineering standards, system reliability, and even aesthetic considerations), but that may have different initial investment costs; different operating, maintenance and repair (OM&R) costs (including water and energy usage); and possibly different lives. (p.1-1)

LCCA is in direct contrast with simple payback time or dynamic payback time method in that it considers the whole lifetime of a project instead of just the payback period. In the setting of rural houses in northern China, it is more suitable and comprehensive than payback time method.

Because of the comprehensiveness and the advantages over other methods in evaluating building design alternatives, quite a few studies have been conducted on assessing energy efficient or green building designs using LCCA. Hasan (1999) optimized the insulation thickness of buildings in Palestine based on LCCA and applied the optimization to Palestine. Wang, Zmeureanu, & Rivard (2005) used life cycle cost (LCC) as the criterion in their optimization model in green building design. Other researches on low energy building design also assessed different designs by their LCCs (Agrawal & Tiwari, 2010; Chel & Tiwari, 2009; Çomaklı & Yüksel, 2003; Jaber & Ajib, 2011; Johnsson, 2009; Kaynakli, 2008; Uygunoğlu & Kecebas, 2011; Yu, Yang, Tian, & Liao, 2009).

2.8. Chapter Summary

Building energy consumption contributes a significant part to the whole energy consumption and will still increase in percentage in China. China has been trying to improve the energy efficiency of building sector and many energy efficient measures have added to existing and newly built buildings. However, it is not the case in the rural areas in northern China. It is desired to develop a series of energy efficient strategies. Through the literature review and the author's experience, the insulation level has been identified as a promising component to improve for the rural houses in northern China. Energyplus is a powerful and suitable energy simulation tool for this research considering its function, the requirement of the research and the author's experience. LCC is used as the criterion to assess building envelopes with different insulation levels.

CHAPTER 3. RESEARCH METHODOLOGY

The methodology presented in this chapter is designed to answer the aforementioned research questions. The study procedure gives an overview of the processes involved in this research. In the second section, the base hypothetical case and evolutionary cases are introduced, which are the subjects of study in this research. The independent variables are described in the third section. The data collection gives the source of data used in the study. The last section is a summary of this chapter.

3.1. Procedure

In order to answer the research questions, the study employs life cycle cost (LCC) analysis to evaluate each design solution for rural houses in China. The analysis begins with a base case, which reflects the current dominant house envelope and indoor air temperature in rural northern China. Evolutionary cases are configured to reflect the improving living standards in rural areas in the future, a part of which involves increasing indoor air comfort level. The research then manipulates the independent variables, the insulation levels of roof and exterior walls, to analyze their effects on the dependent variable: LCC. Design solution with the lowest LCC within one variable manipulation is the optimized one. Sensitivity tests are conducted to take into consideration the fluctuation of energy prices, discount rates, and lifetimes of houses (see *Figure 3.1*).

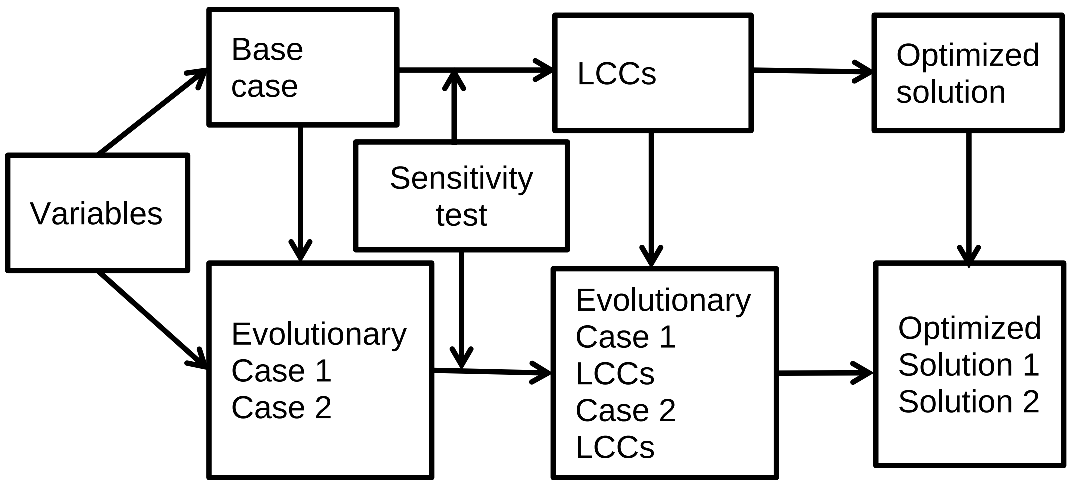

Figure 3.1 Research procedures

3.2. Study Subjects

The study uses quantitative research method with hypothetical case subjects. The hypothetical cases include base case and evolutionary cases. The evolutionary cases account for the improving living standards in the rural areas. By incorporating this element, the study is more generalizable and thus can be used to predict the energy consumption under certain set point temperatures.

3.2.1. Base Case

The base case, which is the starting point of this study, represents the dominant house types and indoor air conditions in rural northern China today (see Table 3.1). The hypothetical case is located in a rural village in Baoding, Hebei Province, China. The altitude and longitude is 39° N and 115° E respectively. This area belongs to the Cold Climate Zone mentioned in Section 1.1. It is in temperate semi-humid and semi-arid continental monsoon climate zone with distinct four seasons. Winter is dry and cold with scarce rain or snow while summer is hot and humid. The heating period (when the daily average temperature is below 5 °C (41 °F)) is 119 days and heating degree days is

2285 °C·d or 4113 °F·d based on an indoor air temperature of 18 °C (64°F). The average temperature is -4.1°C (24.6 °F) in the coldest month and 26.6 °C (80 °F) in the hottest month (Ministry of Construction of the People's Republic of China, 1993).

The weather data is freely available from the U.S. DOE Energy Efficiency and Renewable Energy (2011) website. It has the EPW format especially for the weather data input in EnergyPlus.

The aspect ratios (the ratio of its longer dimension to its shorter dimension) of single houses in rural northern China are mostly between 1.5 and 3.5, depending on how many rooms the houses are designed to have. The depth of a room is between 5 m (16.4 ft) and 8 m (26.2 ft), and the width is between 3 m (9.8 ft) to 5 m (16.4 ft). The rooms are aligned along the width direction (see *Figure 3.2*). Therefore, the more rooms the houses have, the bigger the aspect ratios will be. In the base case, each room is 4 m (13.1 ft) (width) by 6 m (19.7 ft) (depth) and there are five rooms, so the house is 20 m (65.6 ft) by 6 m (19.7 ft). The roof is concrete slab and the wall is 240 mm brick which serves as both structure and "insulation". This type of exterior wall is very common in the Cold Climate Zone in China. In the Severe Cold Climate Zone, the thickness of exterior walls can be 370 mm (14.6 inches), 490 mm (19.3 inches) or even 600 mm (23.6 inches).

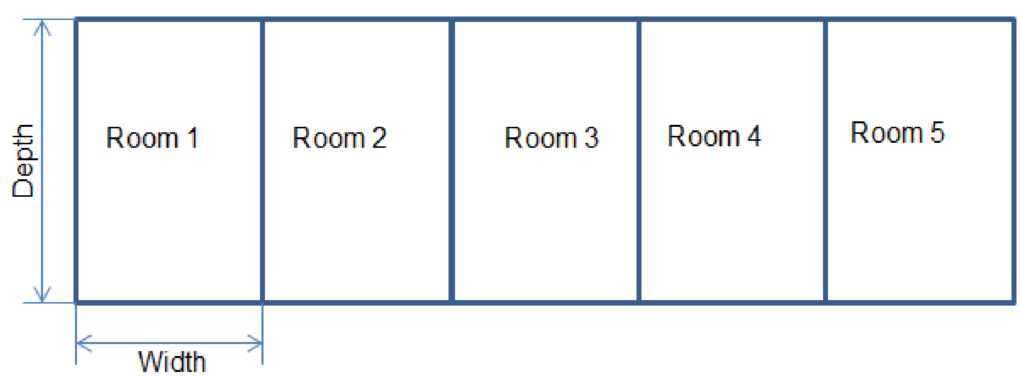

Figure 3.2 Floor plan of the base hypothetical case

According to data from the China Statistical Yearbook 2010 (National Bureau of Statistics of China, 2010), the average number of people per household in rural areas in China was 3.98 in 2009. In this study, there are four occupants in the house (Table 3.1).

Table 3.1*Base hypothetical case configuration*

Parameter name	Parameter value
Location	Baoding, Hebei, China
Building orientation	Plan north: north
Assumed lifetime	30 years
Square footage	120 m^2 (1292 ft^2)
Type of Housing	Single detached
Number of floors	1
Floor height	3 m (9.8 ft) floor to floor, and 2.7 m (8.9 ft) floor to ceiling
Footprint shape	rectangular
Aspect ratio	3.33
Construction type	brick and concrete
Brick wall thickness	240 mm (9.45 inches)
Roof construction	120 mm (4.7 inches) concrete
Ceiling	Gypsum board
Window type	Double pane, and 13 (0.5 inch) mm air
Glazing type	3 mm (1/8 inch) clear
Window to wall ratio	0.35 for south facing walls and no windows on other walls
Window blinds	no
Relative humidity %	30 to 60
Infiltration rate (ACH)	0.51
Cooling energy source	electricity
Heating energy source	coal
Set points °C	heating: 13 °C (55 °F) cooling: 29 °C (84 °F)
Number of occupants	4

The heating set point is 13 °C (55 °F) in the base hypothetical case, which is lower than the lower bound of the range which is between16 °C (61 °F), 24 °C (75 °F) set by Indoor Air Quality Standard GB/T 18883-2002 (Standardization Administration of the People’s Republic of China, 2002). The cooling set point temperature is 29 °C (84 °F). The infiltration rate is set to be

0.51 air changes per house (ACH), as recommended by Energy Conservation Design Standard for Heating New Residential Buildings JGJ26-95. Relative humidity (RH) is controlled to be between 30% and 60%. Please see Appendix D for the detailed input of HVAC system in EnergyPlus.

3.2.2. Evolutionary Cases

The evolutionary cases differ from the base case in that they have higher heating set points. They are meant to reflect the improving living standards. Two evolutionary cases are studied (see Table 3.2).

Table 3.2 *Temperature set points of evolutionary cases*

Evolutionary cases	Temperature set points °C	
	Heating	Cooling
case 1	16 (61 °F)	26 (79 °F)
case 2	18 (64 °F)	23 (73 °F)

3.3. Variables

The dependent variables are the LCCs for each case given a set of independent variables. The independent variables are those that have significant influence on the initial construction costs and the energy consumption during the operation of the house. As discussed in Section 2.4, the building envelope has a significant influence on the energy consumption of buildings. However, the houses in north rural areas in China are not insulated at all which make the building envelop a promising component for energy conservation. Therefore, this research focuses on the following two building envelope variables: exterior wall insulation level and roof insulation level.

3.3.1. Exterior Wall and Roof Insulation Level

Exterior wall and roof insulation level has a significant impact on energy consumption. Increasing the insulation level of the exterior walls and roof will normally increase the energy efficiency of the building. However, high initial construction cost often comes with high insulation level. Wall and roof type is also an important factor because, even if the insulation level is the same, houses with different types of walls and roofs can be very different in their energy consumption. In addition, the construction costs are different for different walls and roofs with the same insulation level. However, since brick walls and concrete roofs are the major construction types for rural houses in China, this research focuses only on brick wall and concrete roof.

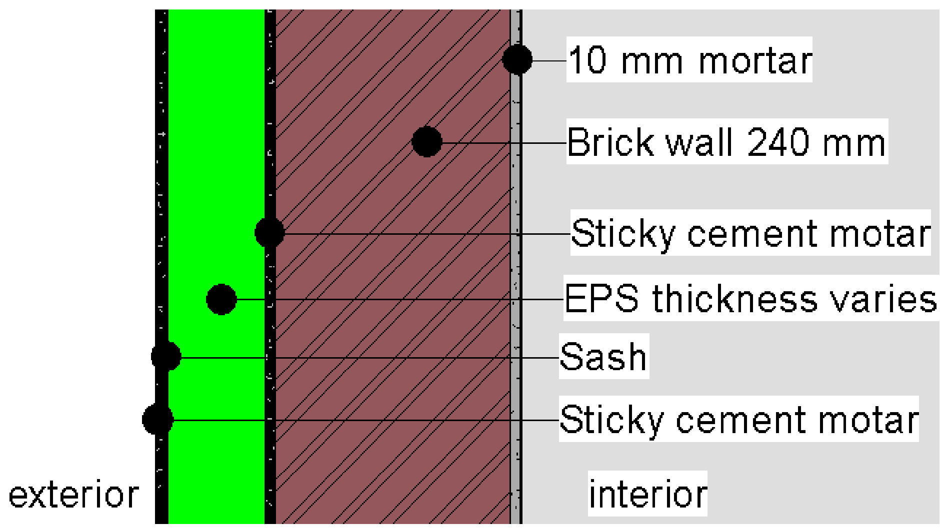

Figure 3.3 Section detail of exterior wall

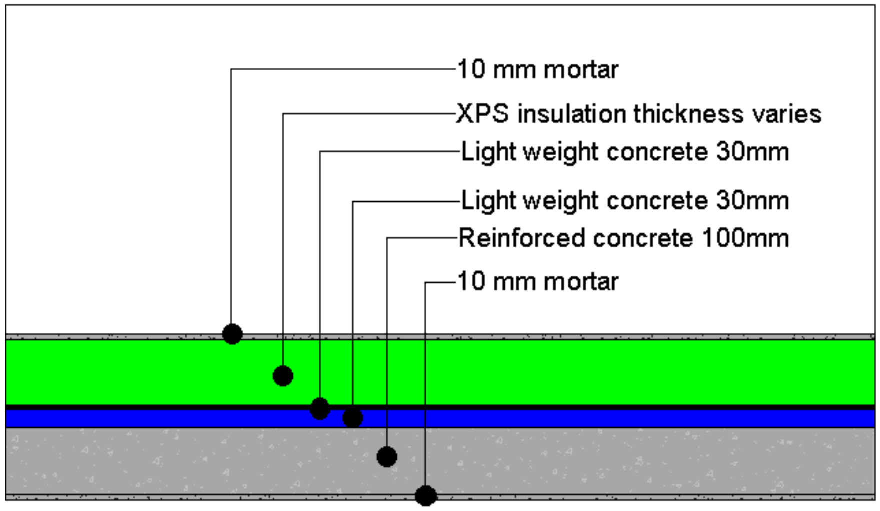

Figure 3.4 Section detail of roof

Table 3.3 *U values of exterior wall and roof with different insulation*

insulation thickness	Wall U value ($W/m^2 \cdot k$)	Roof U value ($W/m^2 \cdot k$)	Wall U value ($Btu/h \cdot ft^2 \cdot °F$)	Roof U value ($Btu/h \cdot ft^2 \cdot °F$)
0	2.042	2.212	11.60	12.56
25	0.831	0.744	4.72	4.23
50	0.521	0.447	2.96	2.54
75	0.38	0.319	2.16	1.81
100	0.299	0.249	1.70	1.41
150	0.209	0.172	1.17	0.977
200	0.161	0.132	0.914	0.750

3.4. Data Collection

3.4.1. Initial Cost and Residual Value

A database for regional construction labor, material and equipment cost is available in China's regional construction authorities. However, a professional estimator (Chen, 2011) was consulted to give an estimation of the cost of insulating wall and roof at different levels (see Table 3.4). The residual value of the insulation is assumed to be zero after the service lifetime.

Table 3.4 *Added initial cost of insulation*

EPS or XPS thickness mm	Wall insulation (EPS) Yuan/m^2	Roof insulation (XPS) Yuan/m^2
25	71.85	11.36
50	77.85	18.86
75	83.85	26.36
100	89.85	33.86
150	101.85	48.86
200	113.85	63.86

Note. Yuan is the currency in China

3.4.2. Energy price

There are two energy sources: electricity and coal. The units used for electricity consumption is KWh, while that for coal consumption is metric ton of coal equivalent (TCE), a conventional value of 7 Gcal (IT) = 29.3076 GJ. The electricity cost is 0.52 Yuan per KWh for residential use according to the Electricity Information Publication (2011). The TCE price is calculated based on power coal with different calorific value in Table 3.5. First, the unit calorific value is calculated. Then, the average of the prices per calis multiplied by 7 Gcal. The result is 959 Yuan per TCE.

Table 3.5 *Power coal prices in Qinghuangdao in March 23, 2011 (CQCOAL, 2011)*

Power coal calorific value (Kcal/Kg)	coal price (Yuan)
4500	585
5000	675
5500	775
5800	825

3.4.3. Discount and Inflation Rate

Five percent is the default discount rate. The study conducts sensitivity tests of various discount rates from 5% to 15%. Since the study is comparing different alternatives, a constant currency method is used. The inflation rate is set to be zero.

3.5. LCC Calculation

Life cycle cost (LCC) in this research is the cost involved in constructing, operating, and disposing of the house. All costs are first converted into present value (PV). Then, the PVs are added up to obtain the LCCs.

$$LCC = I + \sum_{i=1}^{n} \frac{E_i}{(1+d)^i}$$

Where LCC is Life Cycle cost

I is initial cost of installing insulation

n is the service lifetime of the insulation

d is the real discount rate

E_i is the energy cost in year i.

3.6. Chapter Summary

There are two categories of hypothetical cases described in this chapter: base hypothetical case and evolutionary hypothetical cases. They differ in heating and cooling set point temperatures. The base hypothetical case has the set point temperatures that are common in rural northern China today. The evolutionary hypothetical cases, however, have higher standards of set point temperatures. The test criteria of the hypothetical cases under various insulation levels are the LCCs of them.

CHAPTER 4. RESULTS AND ANALYSIS

4.1. Total Additional Investment of Various Insulation Levels

The total additional investment is the additional investment that occurs when insulation is added to the design. It includes not only the insulation material cost, but also costs of other measures that are necessary to install the insulation. As can be seen in Table 4.1, for wall insulation, the EPS material cost is only a fraction of the total cost. However, as the thickness increases, the material costs assume a higher percentage of the total cost. This is because other measures do not change much with the increase in EPS thickness. In roof insulation, however, the material costs constitute most of the total cost because installation of XPS on roof does not require as many additional measures.

Table 4.1*Total investment of various insulation levels*

EPS or XPS thickness	Wall insulation (EPS)		Roof insulation (XPS)	
	EPS material cost	Total cost	XPS material cost	Total cost
25 mm	¥936	¥11,209	¥900	¥1,363
50 mm	¥1,872	¥12,145	¥1,800	¥2,263
75 mm	¥2,808	¥13,081	¥2,700	¥3,163
100 mm	¥3,744	¥14,017	¥3,600	¥4,063
150 mm	¥5,616	¥15,889	¥5,400	¥5,863
200 mm	¥7,488	¥17,761	¥7,200	¥7,663

4.2. Base Case Results and Analysis

4.2.1. Energy Consumptions of All Insulation Scenarios

The energy consumptions shown in *Figure 4.1* and *Figure 4.2* are heating and cooling energy consumption. In the case without any insulation, the cooling electricity is 2415 KWh (8.24 MBtu) and the heating coal consumption is 0.423 metric ton of coal equivalent (TCE). With 25 mm (1 inch) EPS wall insulation and 25 mm roof insulation, the cooling electricity consumption drops to 1195 KWh (4.08 MBtu) and the heating coal consumption decreases to 0.053 TCE. These savings are very significant.

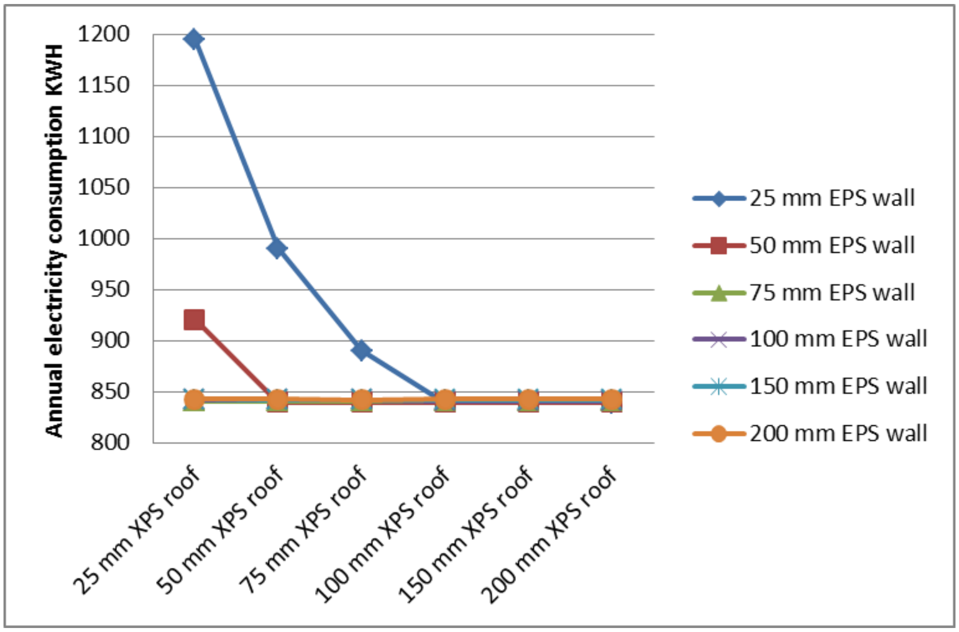

Figure 4.1 Annual electricity consumption in base case

When it comes to high insulation levels, however, the savings are much smaller. When the thickness of both wall EPS and roof XPS are more than 50 mm (2 inches), the electricity consumption stays at around 840 KWh (2.87 MBtu) and the coal consumption stays at around 0.023 TCE. There is a diminishing effect of thicker insulation on reducing energy consumption.

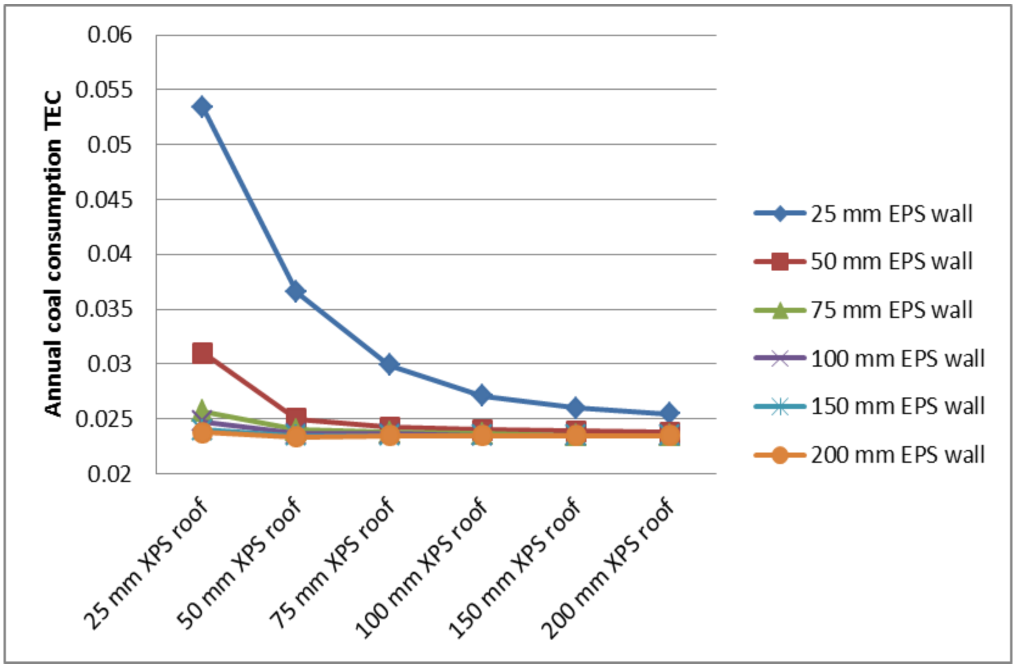

Figure 4.2 Annual coal consumption in base case

4.2.2. Best Insulation Scenario for Base Case

The test criteria are the LCCs of all insulation scenarios. The one with the lowest LCC is the optimal insulation scenario. *Figure 4.3* shows the LCCs of all insulation scenarios including the one without any insulation. The lowest LCC is ¥ 21,714 (¥ is the symbol for Yuan) with 50 mm (2 inches) EPS wall and 25 mm (1 inch) XPS roof. The LCC of the scenario without any insulation is ¥ 26,808.

All the lines, except the 25 mm (1 inch) EPS wall line, go up with the increase in roof insulation level because the energy consumption does not decrease with the increasing insulation while the initial cost increases.

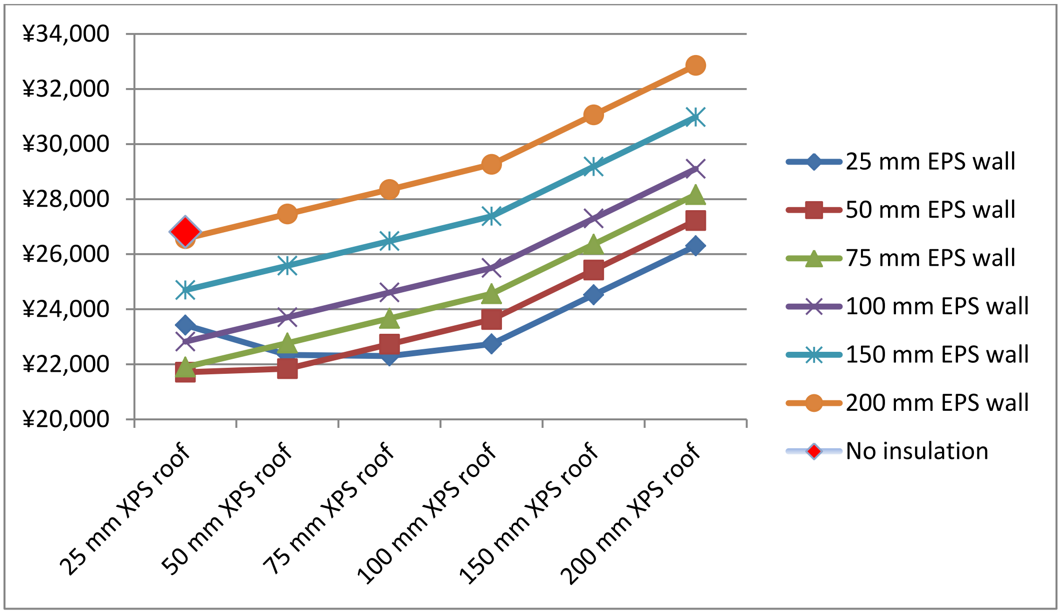

Figure 4.3 LCCs of all insulation scenarios of base case

4.2.3. Sensitivity Test on Energy Prices

Energy prices are directly related to the energy cost during the lifetime of the rural house. This test investigates the impacts of energy price escalation rates on the optimal insulation scenarios. The energy price escalation rate is the real escalation rate which excludes general inflation.

Table 4.2 *Optimal insulation scenarios under various energy escalation rates of base case*

Energy escalation rates	1%	2%	3%	4%
Minimum LCCs	¥22,258	¥23,329	¥24,507	¥25,906
Insulation scenarios	50 mm EPS wall, 25 mm XPS roof	50 mm EPS wall, 50 mm XPS roof	50 mm EPS wall, 50 mm XPS roof	50 mm EPS wall, 50 mm XPS roof

If the energy price escalation rate is 1%, the optimal insulation scenario is 50 mm (2 inches) EPS wall and 25 mm (1 inch) XPS roof, which is the same as the result in 4.2.2 (Table 4.2). Under 2%, 3%, and 4% energy escalation rates, the optimal insulation scenarios are all 50 mm (2 inches) EPS wall and 50 mm XPS roof. High escalation rates are in favor of high insulation scenarios.

4.2.4. Sensitivity Test on Lifetimes

Lifetime is assumed to be 30 years in the previous analysis. However, this can vary sharply depending on environment and construction quality. Therefore, this test studies optimal insulation scenarios under five different lifetimes: 20 years, 25 years, 30 years (assumed), 35 years, and 40 years.

Table 4.3 *Optimal insulation scenarios of different lifetimes of base case*

Lifetime	20 years	25 years	30 years	35 years	40 years
Minimum LCC	¥20,161	¥21,032	¥21,714	¥22,249	¥22,668
Insulation scenarios	50 mm EPS wall, 25 mm XPS roof	50 mm EPS wall, 25 mm XPS roof	50 mm EPS wall, 25 mm XPS roof	50 mm EPS wall, 25 mm XPS roof	50 mm EPS wall, 25 mm XPS roof

The study shows that the optimal insulation scenario does not change from the result in 4.22. The optimal insulation scenarios under all lifetimes are 50 mm (2 inches) EPS wall and 25 mm (1 inch) XPS roof. The LCCs, however, do increase when the lifetime is longer (Table 4.3).

4.2.5. Sensitivity Test on Discount Rates

Discount rate is assumed to be 5% in the previous analysis. In the sensitivity test, discount rates from 5% to 15% are analyzed. As shown in Table 4.4, if the discount rate is from 5% to 8%, the optimal insulation scenario is 50 mm (2 inches) EPS wall and 25 mm (1 inch) XPS roof. When the discount rate is higher than 9%, the optimal scenario is no insulation at all.

Table 4.4 *Optimal insulation scenarios and discount rates of base case*

Discount rates %	Minimum LCC	Insulation scenario
5	¥21,714	50 mm EPS wall, 25 mm XPS roof
6	¥20,926	50 mm EPS wall, 25 mm XPS roof
7	¥20,258	50 mm EPS wall, 25 mm XPS roof
8	¥19,689	50 mm EPS wall, 25 mm XPS roof
9	¥18,596	No insulation
10	¥17,219	No insulation
11	¥16,024	No insulation
12	¥14,980	No insulation
13	¥14,064	No insulation
14	¥13,255	No insulation
15	¥12,537	No insulation

This indicates that if the home owner has an expected rate of return equal to or higher than 9%, the investment on insulating the building envelope is not a good option. However, if the home-owner simply deposits the money in the bank in China, with interest rates lower than 8 percent, the investment on insulating the house is a better option.

4.3. Evolutionary Cases Results and Analysis

4.3.1. Energy Consumptions of All Insulation Scenarios

In evolutionary case 1, in which heating temperature set point is 16 °C (61 °F) and cooling is 26 °C (79 °F), the electricity consumption used for cooling is 3494 KWh and the coal consumption for heating is 1.419 TCE without any insulation. In evolutionary case 2, in which heating temperature set point is 18 °C (64 °F) and cooling is 23°C (73 °F), the electricity consumption used for cooling is 7690 KWh (26.25 MBtu) and the coal consumption for heating is 2.481 TCE without any insulation. The energy consumption of the two evolutionary cases is much higher than that of the base case. Therefore, the occupants’ preference on the set point temperatures is crucial in the energy consumption of the house.

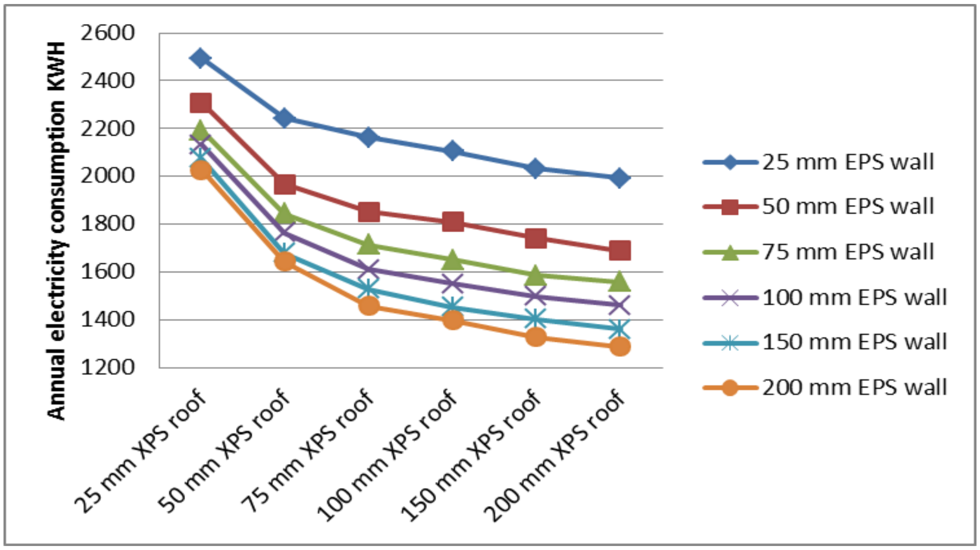

Figure 4.4 Annual electricity consumption in evolutionary case 1

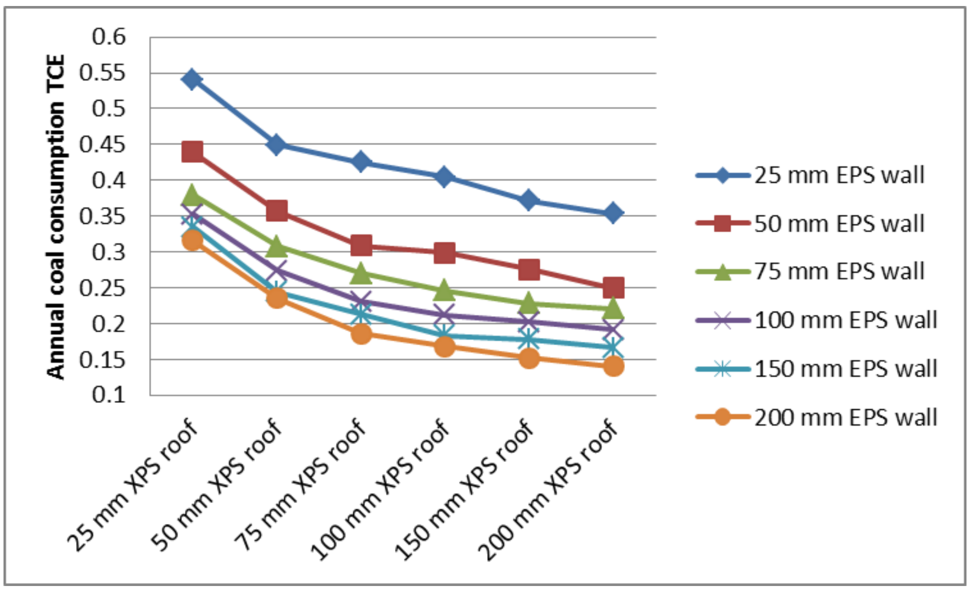

Figure 4.5 Annual coal consumption in evolutionary case 1

This indicates that there will be a huge increase in energy consumption in the rural areas if the indoor air temperature is maintained at the levels recommended by Indoor Air Quality Standard GB/T 18883-2002 (Standardization Administration of the People's Republic of China, 2002).

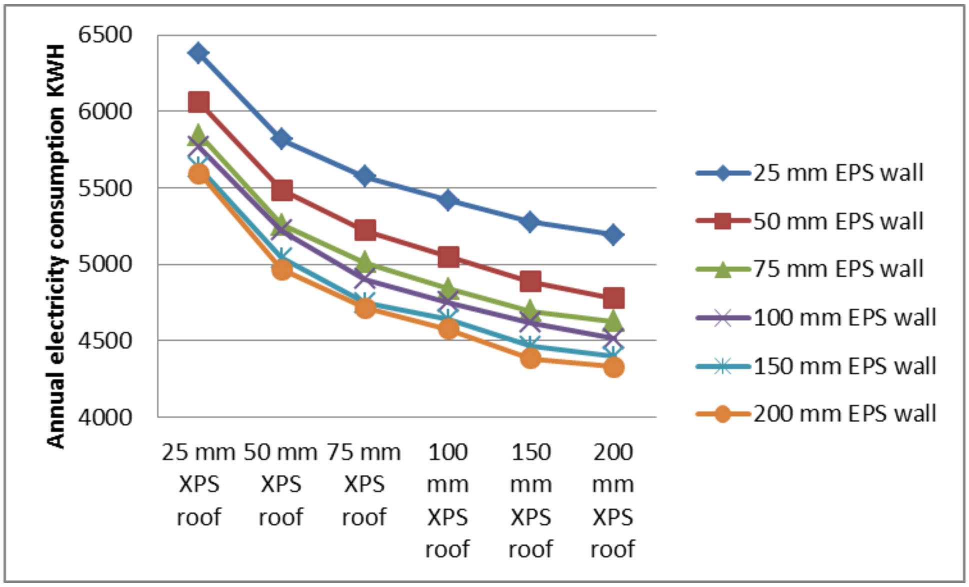

Figure 4.6 Annual electricity consumption in revolutionary case 2

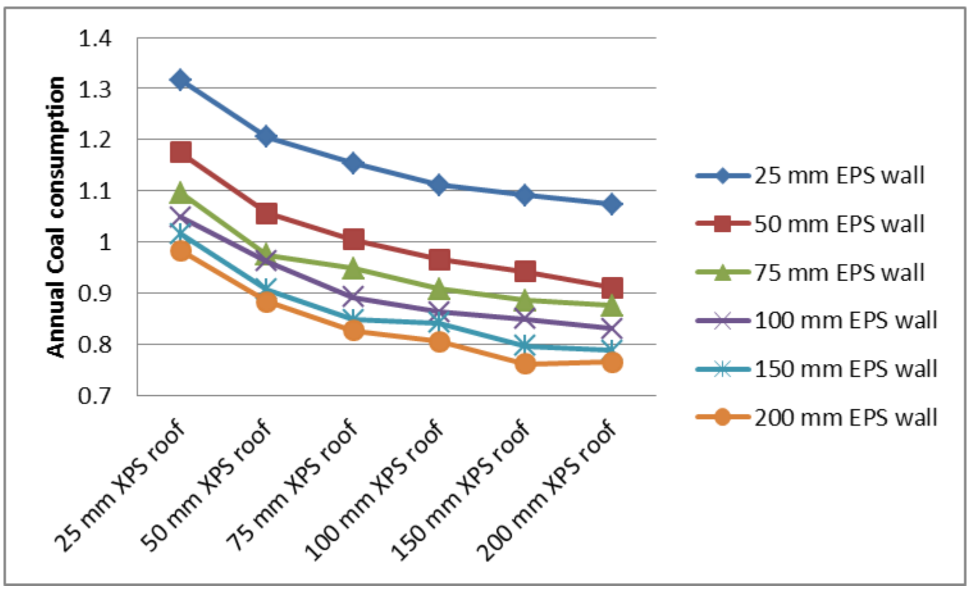

Figure 4.7 Annual coal consumption in evolutionary case 2

The energy consumption in the two evolutionary cases is different from that in the base case. In the base case, the energy consumption stays the same with high levels of insulation. In the two evolutionary cases, however, the energy consumption decreases, even when the insulation reaches a high level, for example 150 mm (5.9 inches) EPS wall and 150 mm XPS roof (see *Figure 4.4,*

Figure 4.5, Figure 4.6, and *Figure 4.7*). In the two evolutionary cases, thicker insulation has more value than that in the base case in reducing energy consumption.

4.3.2. Best Insulation Scenarios for Evolutionary Cases

In evolutionary case 1, the optimal insulation scenario is 100 mm (3.9 inches) EPS wall and 75 mm (3 inches) XPS roof, the LCC of which is ¥34,252. The LCC of the one without insulation is ¥51,273, which is at least ¥10,000 higher than all scenarios with insulation (see *Figure 4.8*). This means that any insulation scenarios in this research are cost effective from a LCC perspective.

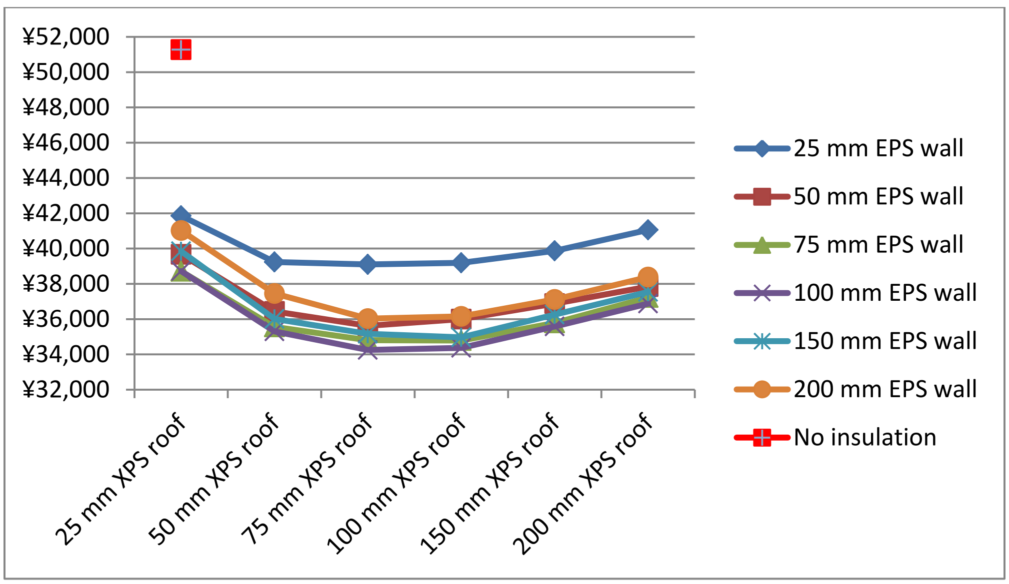

Figure 4.8 LCCs of all insulation scenarios of evolutionary case 1

In evolutionary case 2, the optimal insulation scenario is 100 mm (3.9 inches) EPS wall and 100 mm XPS roof and its LCC is ¥71,291. The LCC of the one without insulation is ¥102,903, which is at least ¥15,000 higher than all the scenarios with insulation (see *Figure 4.9*).

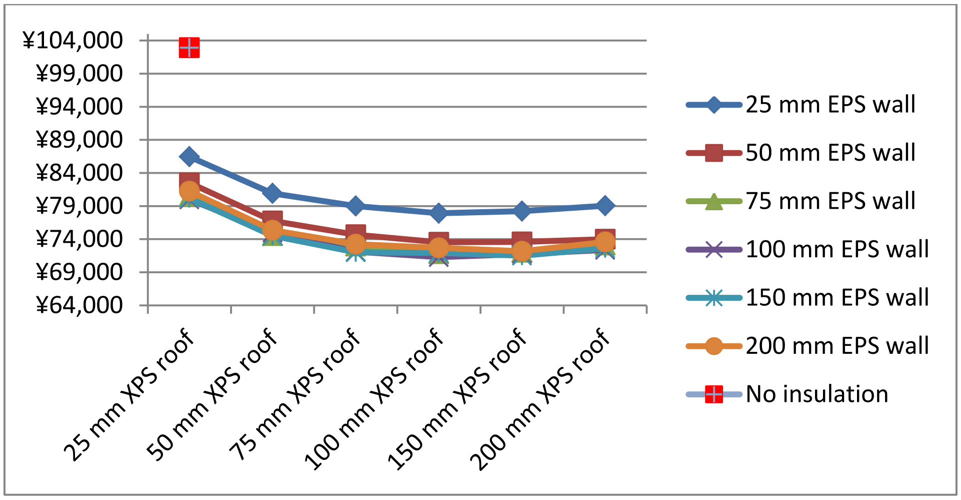

Figure 4.9 LCCs of all insulation scenarios of evolutionary case 2

4.3.3. Sensitivity Test on Energy Prices

For evolutionary case 1, when the energy escalation rate is 1%, the optimal insulation scenario is 100 mm (3.9 inches) EPS wall and 75 mm (3 inches) XPS roof, which is the same as the result in 4.3.2. The LCC, however, increases to ¥35,383 from ¥34,252. When the energy escalation rate is 2%, 3% and 4%, the best insulation scenario is 100 mm (3.9 inches) EPS wall and 100 mm XPS roof (see Table 4.5).

For evolutionary case 2, the optimal insulation scenario is 150 mm (5.9 inches) EPS wall, 150 mm XPS roof under all studied energy price escalation rates (see Table 4.6). This is different from the result in 4.3.2.

Table 4.5 *Optimal insulation scenarios under various energy escalation rates of evolutionary case 1*

Energy escalation rates	1%	2%	3%	4%
Minimum LCCs	¥35,383	¥37,630	¥40,210	¥43,177
Insulation scenarios	100 mm EPS wall, 75 mm XPS roof	100 mm EPS wall, 100 mm XPS roof	100 mm EPS wall, 100 mm XPS roof	100 mm EPS wall, 100 mm XPS roof

Table 4.6 *Optimal insulation scenarios under various energy escalation rates of evolutionary case 2*

Energy escalation rates	1%	2%	3%	4%
Minimum LCCs	¥74,797	¥81,456	¥89,338	¥98,699
Insulation scenarios	150 mm EPS wall, 150 mm XPS roof	150 mm EPS wall, 150 mm XPS roof	150 mm EPS wall, 150 mm XPS roof	150 mm EPS wall, 150 mm XPS roof

4.3.4. Sensitivity Test on Lifetimes

In evolutionary case 1, the optimal insulation scenario does not change with various lifetimes (see Table 4.7). In evolutionary case 2, however, the optimal insulation scenario changes from 100 mm (3.9 inches) EPS wall and 100 mm XPS roof to 150 mm (5.9 inches) EPS wall and 150 mm XPS roof when the lifetimes are longer than 35 years (see Table 4.8).

Table 4.7*Optimal insulation scenarios of different lifetimes of evolutionary case 1*

Lifetime	20 years	25 years	30 years	35 years	40 years
Minimum LCCs	¥31,021	¥32,833	¥34,252	¥35,364	¥36,235
Insulation scenarios	100 mm EPS wall, 75 mm XPS roof	100 mm EPS wall, 75 mm XPS roof	100 mm EPS wall, 75 mm XPS roof	100 mm EPS wall, 75 mm XPS roof	100 mm EPS wall, 75 mm XPS roof

Based on the sensitivity test, the lifetime does have an effect on the optimal insulation scenario, although it does not change the optimal scenario in evolutionary case 1.

Table 4.8 *Optimal insulation scenarios of different lifetimes of evolutionary case 2*

Lifetime	20 years	25 years	30 years	35 years	40 years
Minimum LCC	¥61,221	¥66,868	¥71,291	¥74,740	¥77,278
Insulation scenarios	100 mm EPS wall, 100 mm XPS roof	100 mm EPS wall, 100 mm XPS roof	100 mm EPS wall, 100 mm XPS roof	150 mm EPS wall, 150 mm XPS roof	150 mm EPS wall, 150 mm XPS roof

4.3.5. Sensitivity Test on Discount Rates

In evolutionary case 1, the optimal insulation scenario stays the same as the result in 4.3.2 until the discount rate is 10% (see Table 4.9). The optimal insulation scenario is 75 mm (3 inches) EPS wall and 75 mm XPS roof when the insulation rate is 11% and 12%. For discount rates of 13%, 14%, and 15%, the optimal insulation scenarios are 75 mm (3 inches) EPS wall and 50 mm (2 inches) XPS roof, 50 mm EPS wall and 50 mm XPS roof, and no insulation respectively.

Table 4.9 *Optimal insulation scenarios and discount rates of evolutionary case 1*

Discount rate %	Minimum LCC	Insulation scenario
5	¥34,252	100 mm EPS wall, 75 mm XPS roof
6	¥32,611	100 mm EPS wall, 75 mm XPS roof
7	¥31,222	100 mm EPS wall, 75 mm XPS roof
8	¥30,038	100 mm EPS wall, 75 mm XPS roof
9	¥29,022	100 mm EPS wall, 75 mm XPS roof
10	¥28,145	100 mm EPS wall, 75 mm XPS roof
11	¥27,341	75 mm EPS wall, 75 mm XPS roof
12	¥26,618	75 mm EPS wall, 75 mm XPS roof
13	¥25,950	75 mm EPS wall, 50 mm XPS roof
14	¥25,301	50 mm EPS wall, 50 mm XPS roof
15	¥23,978	No insulation

Table 4.10 *Optimal insulation scenarios and discount rates of evolutionary case 2*

Discount rate %	Minimum LCC	Insulation scenarios
5	¥71,291	100 mm EPS wall, 100 mm XPS roof
6	¥66,177	100 mm EPS wall, 100 mm XPS roof
7	¥61,847	100 mm EPS wall, 100 mm XPS roof
8	¥58,156	100 mm EPS wall, 100 mm XPS roof
9	¥54,990	100 mm EPS wall, 100 mm XPS roof
10	¥52,238	75 mm EPS wall, 100 mm XPS roof
11	¥49,802	75 mm EPS wall, 100 mm XPS roof
12	¥47,675	75 mm EPS wall, 100 mm XPS roof
13	¥45,807	75 mm EPS wall, 100 mm XPS roof
14	¥44,159	75 mm EPS wall, 100 mm XPS roof
15	¥42,696	75 mm EPS wall, 100 mm XPS roof

In evolutionary case 2, the optimal insulation scenario stays the same as the result in 4.3.2 until the discount rate is 9% (see Table 4.10). For discount rates of 10% to 15%, the optimal insulation scenario is 75 mm (3 inches) EPS wall and 100 mm (3.9 inches) XPS roof.

4.4. Chapter Summary

This chapter shows the LCC analysis results of the base case and two evolutionary cases. For the base case, the best insulation scenario is 50 mm (2 inches) EPS wall and 25 mm (1 inch) XPS roof. In the sensitivity tests of base case, when the energy price has an escalation rate of 2% to 4% through the lifetime of the house, the best insulation scenario increases to 50 mm (2 inches) EPS wall and 50 mm XPS roof. The sensitivity test on lifetime shows no effect on the base case. Increasing discount rates diminish the present value of energy saved in the future and thus are in favor of lower levels of insulation scenarios.

The best insulation scenarios are 100 mm (3.9 inches) EPS wall and 75 mm (3 inches) XPS roof and 100 mm (3.9 inches) EPS wall and 100 mm XPS roof for evolutionary case 1 and case 2 respectively. The best insulation scenario is very sensitive to energy price escalation rates, which is the same as in the base case. Longer lifetimes (35 and 40 years) have changed the best insulation scenario to 150 mm (5.9 inches) EPS wall and 150 mm XPS roof in evolutionary case 2. Increasing discount rate is reducing the best insulation levels in both cases.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Findings

5.1.1. Findings on Base Case

In the base case, the heating set point temperature is 13 °C (55 °F) and the cooling set point temperature is 29 °C (84 °F). The optimal insulation scenario is 50 mm (2 inches) EPS wall and 25 mm (1 inch) XPS roof, the life cycle cost (LCC) of which is ¥ 21,714. Some high insulation scenarios are not cost effective from the LCC perspective compared to no insulation given the fact that the annual energy consumption is so low. There is not much room to reduce energy consumption.

In the sensitivity test, the studied lifetimes do not change the best insulation scenarios. If the expected lifetime of the house is between the 20 years and 40 years, the optimal insulation scenario is 50 mm (2 inches) EPS wall and 25 mm (1 inch) XPS roof.

When the energy price escalation rate is 2% or below, the optimal insulation scenario stays the same. However, when the escalation rate is 3% and 4%, the best insulation scenario increases to a higher level, 50 mm (2 inches) EPS wall and 50 mm XPS roof. It indicates that higher expectations of energy prices favor higher insulation scenarios because the savings on energy tend to lead to more savings on LCC.

The sensitivity on discount rate shows that from 6% to 8%, the optimal insulation scenario is the same as that for 5% discount rate. When the discount rate is 9% or above, the one without insulation has the minimum LCC.

5.1.2. Findings on Evolutionary Cases

The optimal insulation scenario for evolutionary case 1 is 100 (3.9 inches) mm EPS wall and 75 mm (3 inches) XPS roof and that for evolutionary case 2 is 100 mm (3.9 inches) EPS wall and 100 mm XPS roof. They are higher than the optimal insulation scenario of the base case due to energy demand for greater occupant comfort.

In the sensitivity test on energy price escalation rate, the optimal insulation scenario increases to 100 mm (3.9 inches) EPS wall and 100 mm XPS roof when the rate is 2% or above for evolutionary case 1. For evolutionary case 2, however, the optimal insulation scenario does not change in the studied energy price escalation rates.

For evolutionary case 1, the variation in lifetime does not change the optimal insulation scenario. For evolutionary case 2, however, when the lifetime is 35 years and 40 years, the best insulation scenario increases to 150 mm (5.9 inches) EPS wall and 150 mm XPS roof. The best insulation scenario is the same for lifetimes under 20 years, 25 years, and 30 years.

The discount rate has a negative relationship to the level of the insulation scenario. A high insulation rate is in favor of a low insulation scenario. In evolutionary case 1, the optimal insulation scenario drops from 100 mm EPS (3.9 inches) wall and 75 mm (3 inches) XPS roof to no insulation when the discount rate increases from 5% to 15%. The evolutionary case 2 is less sensitive to variation in discount. The optimal insulation scenario drops from 100 mm (3.9 inches) EPS wall and 100 mm XPS roof to 75 mm (3 inches) EPS wall and 100 mm XPS roof when the discount rate increases from 5% to 15%.

5.2. Determinants in Insulation Level Selection

In this study, the most critical determinant is the setting point temperatures. From the base case to the evolutionary case 2, the optimal insulation scenario increases from 50 mm (2 inches) EPS wall and 25 mm (1 inch) XPS roof to 100 mm (3.9 inches) EPS wall and 100 mm XPS roof. Assuming there is no active heating and cooling required, the insulation will not save any energy. If there is much active heating and cooling, the insulation has a better chance of reducing the energy consumption used in heating and cooling. Therefore, in rural housing design, an assessment of the residents' potential in using active heating and cooling is necessary to achieve the optimal envelope design.

Another important determinant is the cooling and heating energy price, both current and future. Although a significant amount of energy will be reduced by adding insulation to the rural housing design, it is not necessarily cost effective. If the energy is very cheap, there is a high potential that the savings in energy cost is less than the additional cost of adding more insulation to the housing design. Therefore, energy price must be taken into consideration when designing the rural house envelope.

The third determinant is the expected lifetime of the rural house being designed. In the base case and evolutionary case 1, the lifetime does not change the optimal insulation scenario. This is because higher insulation scenarios do not have enough time to pay off their higher initial cost, and the differences in LCCs compared to the optimal scenario become smaller and smaller with the increase of lifetime. In evolutionary case 2, the longer lifetime changes the optimal insulation scenario.

The fourth determinant is the discount rate used in the LCC calculation. In this research, the optimal insulation scenario is extremely sensitive to discount rate variations. A well-selected and precise discount rate is very important to the selection of insulation scenarios in the design process.

Location is another determinant in designing building envelope insulation. However, in this study, the location is fixed and the effect of it on the insulation level is not tested.

5.3. Recommendations and Future Studies

In this research, the best insulation scenarios range from no insulation to as high as 150 mm (5.9 inches) EPS wall and 150 mm XPS roof. In reality, the house types, footage, HVAC systems, locations, and living patterns are quite different from each other. It is really hard to recommend an exact insulation level for a specific household based on this research.

However, some general recommendations for households in rural areas can be drawn from the study. First, it is generally cost effective from the LCC's perspective to add 50 mm (2 inches) to100 mm (3.9 inches) EPS insulation in the exterior wall and 50 mm (2 inches) to 100 mm (3.9 inches) XPS insulation in the roof when building new houses. Although in the base case, the best insulation scenario is 50 mm (2 inches) EPS wall and 25 mm (1 inch) XPS roof, it is reasonable to predict that the indoor air temperature standard will soon surpass the level in the base case. Therefore, it is more advisory to draw the recommendation based on the two evolutionary cases. In view of the increasing energy price, the best insulation is 75 mm (3 inches) to 100 mm (4 inches) EPS wall and 75 mm to 100 mm XPS roof.

Second, the above recommendation on insulation levels is a general guideline, it is highly recommended to conduct a specific simulation at least on the same type of houses with similar household (living pattern) within the same location. A case by case analysis is desired on each design when possible. In addition, the insulation materials are not limited to XPS and EPS used in this research. The design team should choose the insulation material on a case by case basis.

In view of the limitations of this research, several future research perspectives are necessary and promising in making the results more solid and generalizable:

First, the current energy consumption pattern or living standards of households in northern rural areas in China and its trend in the future should be studied. In this research, the indoor air temperatures in base case and future cases are all assumed or based on the author's observation. This is the basis for this research and if not reflecting the real situation, will make the results not applicable. In addition, a prediction in the future energy consumption pattern can provide a basis for a better model which fits the improving living standards well.

Second, validation of the energy simulation model against field energy readings is necessary. Although EnergyPlus has been validated by numerous simulations, the inputs in the model affect the results a lot. Even a small variation can yield significantly different results. A validation will not only improve the reliability of the results by the simulation, it will also pinpoint the sensitive parameters in the inputs.

Third, government's regulations and stimulus are necessary and useful in facilitating the implementation of energy conservation measures. As discussed in Section 2.7, this thesis only considers the costs and benefits related to a household. A more complete energy conservation assessment model, taking into consideration of the environment, unemployment, tax, etc., is useful for providing recommendations to government regulators.

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APPENDICES

Appendix A. Results of Sensitivity Test on Discount Rate

Table A.1 *Life cycle costs of all insulation scenarios with different discount rates of base case*

Wall EPS thickness (mm)	Roof XPS thickness (mm)	LCC 5%	LCC 6%	LCC 7%	LCC 8%	LCC 9%	LCC 10%	LCC 11%	LCC 12%	LCC 13%	LCC 14%	LCC 15%
0	0	26808	24232	22050	20191	18596	17219	16024	14980	14064	13255	12537
25	25	23424	22381	21498	20745	20099	19542	19058	18636	18265	17937	17647
25	50	22343	21490	20769	20153	19625	19170	18774	18429	18126	17858	17620
25	75	22301	21539	20894	20344	19872	19465	19111	18803	18532	18292	18080
25	100	22738	22020	21413	20895	20451	20067	19734	19444	19189	18963	18763
25	150	24521	23805	23199	22682	22239	21856	21524	21234	20980	20755	20555
25	200	26305	25591	24986	24470	24028	23646	23315	23025	22771	22547	22348
50	25	21714	20926	20258	19689	19200	18779	18413	18094	17813	17565	17346
50	50	21842	21127	20522	20007	19564	19183	18851	18562	18308	18083	17884
50	75	22730	22017	21413	20898	20456	20075	19744	19455	19202	18978	18779
50	100	23626	22913	22310	21795	21354	20973	20642	20353	20100	19876	19677
50	150	25425	24712	24108	23594	23152	22772	22441	22152	21899	21675	21476
50	200	27223	26510	25907	25392	24951	24570	24240	23951	23698	23474	23275
75	25	21897	21181	20575	20057	19614	19231	18899	18609	18354	18129	17930
75	50	22771	22057	21453	20937	20496	20114	19783	19494	19240	19016	18817
75	75	23667	22954	22349	21835	21393	21012	20681	20392	20138	19914	19715
75	100	24565	23852	23248	22733	22292	21910	21580	21291	21037	20813	20614
75	150	26363	25650	25046	24532	24090	23709	23378	23090	22836	22612	22414
75	200	28163	27450	26846	26332	25890	25509	25178	24890	24636	24412	24214
100	25	22827	22111	21505	20988	20545	20163	19831	19541	19286	19062	18862
100	50	23709	22995	22391	21875	21433	21052	20721	20431	20177	19953	19754

Table A.1 *Life cycle costs of all insulation scenarios with different discount rates of base case (continued)*

Wall EPS thickness (mm)	Roof XPS thickness (mm)	LCC 5%	LCC 6%	LCC 7%	LCC 8%	LCC 9%	LCC 10%	LCC 11%	LCC 12%	LCC 13%	LCC 14%	LCC 15%
100	75	24609	23895	23291	22775	22333	21952	21621	21331	21077	20853	20654
100	100	25499	24786	24182	23668	23226	22845	22514	22226	21972	21748	21550
100	150	27299	26586	25982	25468	25026	24645	24314	24026	23772	23548	23350
100	200	29099	28386	27782	27268	26826	26445	26114	25826	25572	25348	25150
150	25	24696	23980	23374	22858	22415	22033	21701	21411	21157	20932	20733
150	50	25580	24866	24261	23746	23304	22923	22592	22302	22048	21824	21625
150	75	26480	25766	25161	24646	24204	23823	23492	23202	22948	22724	22525
150	100	27380	26666	26061	25546	25104	24723	24392	24102	23848	23624	23425
150	150	29180	28466	27861	27346	26904	26523	26192	25902	25648	25424	25225
150	200	30980	30266	29661	29146	28704	28323	27992	27702	27448	27224	27025
200	25	26564	25849	25243	24727	24285	23902	23571	23281	23027	22802	22603
200	50	27458	26744	26139	25623	25181	24799	24467	24178	23924	23700	23500
200	75	28352	27638	27033	26518	26076	25695	25364	25074	24820	24596	24397
200	100	29260	28545	27940	27424	26982	26600	26269	25979	25725	25500	25301
200	150	31060	30345	29740	29224	28782	28400	28069	27779	27525	27300	27101
200	200	32860	32145	31540	31024	30582	30200	29869	29579	29325	29100	28901

Table A.2 Life cycle costs of all insulation scenarios with different discount rates of evolutionary case 1

Wall EPS thickness (mm)	Roof XPS thickness (mm)	LCC 5%	LCC 6%	LCC 7%	LCC 8%	LCC 9%	LCC 10%	LCC 11%	LCC 12%	LCC 13%	LCC 14%	LCC 15%
0	0	51273	46346	42173	38616	35565	32932	30647	28651	26898	25351	23978
25	25	41854	39040	36657	34626	32883	31380	30074	28934	27933	27050	26266
25	50	39241	36764	34667	32880	31346	30023	28874	27871	26990	26213	25523
25	75	39098	36722	34710	32995	31523	30254	29151	28189	27343	26597	25935
25	100	39194	36895	34948	33289	31865	30637	29570	28639	27821	27100	26459
25	150	39868	37678	35822	34241	32885	31714	30698	29810	29031	28343	27733
25	200	41059	38927	37121	35582	34262	33122	32133	31270	30511	29842	29248
50	25	39670	37156	35026	33212	31655	30312	29145	28127	27232	26443	25743
50	50	36439	34322	32529	31001	29690	28559	27576	26719	25966	25301	24711
50	75	35617	33665	32012	30604	29395	28352	27447	26656	25962	25349	24806
50	100	36003	34101	32490	31117	29939	28922	28040	27269	26593	25995	25465
50	150	36878	35064	33529	32220	31097	30128	29287	28552	27907	27338	26832
50	200	37838	36105	34638	33387	32314	31389	30585	29883	29266	28722	28240
75	25	38715	36382	34407	32723	31279	30033	28951	28006	27176	26444	25794
75	50	35560	33618	31972	30570	29367	28329	27428	26641	25950	25339	24798
75	75	34809	33025	31514	30226	29122	28168	27341	26618	25983	25423	24926
75	100	34786	33090	31655	30431	29381	28475	27689	27002	26399	25867	25394
75	150	35781	34163	32793	31625	30623	29758	29008	28352	27777	27269	26818
75	200	37228	35643	34302	33159	32178	31331	30596	29955	29391	28894	28453
100	25	38724	36481	34581	32962	31573	30374	29333	28424	27626	26922	26297
100	50	35302	33474	31926	30606	29474	28498	27650	26909	26259	25685	25176

Table A.2*Life cycle costs of all insulation scenarios with different discount rates of evolutionary case 1 (continued)*

Wall EPS thickness (mm)	Roof XPS thickness (mm)	LCC 5%	LCC 6%	LCC 7%	LCC 8%	LCC 9%	LCC 10%	LCC 11%	LCC 12%	LCC 13%	LCC 14%	LCC 15%
100	75	34252	32611	31222	30038	29022	28145	27384	26720	26136	25621	25164
100	100	34370	32804	31479	30349	29379	28543	27817	27182	26626	26134	25698
100	150	35587	34077	32799	31710	30775	29968	29268	28657	28120	27646	27225
100	200	36881	35420	34183	33128	32224	31443	30766	30174	29654	29196	28789
150	25	39843	37672	35833	34266	32922	31762	30755	29876	29103	28422	27817
150	50	36012	34296	32842	31603	30541	29624	28827	28132	27522	26983	26504
150	75	35164	33616	32304	31187	30228	29401	28682	28055	27504	27018	26587
150	100	34968	33525	32303	31261	30368	29596	28927	28342	27829	27376	26974
150	150	36259	34865	33684	32678	31815	31070	30423	29858	29362	28924	28536
150	200	37542	36197	35059	34088	33256	32537	31914	31369	30891	30469	30094
200	25	41018	38914	37132	35614	34311	33187	32210	31358	30610	29949	29363
200	50	37447	35773	34355	33146	32110	31215	30438	29760	29164	28638	28172
200	75	36026	34574	33345	32298	31399	30624	29950	29362	28846	28391	27986
200	100	36151	34774	33608	32614	31762	31026	30387	29830	29340	28908	28524
200	150	37114	35818	34720	33784	32981	32289	31687	31162	30701	30294	29933
200	200	38385	37139	36085	35185	34414	33749	33171	32666	32223	31832	31485

Table A.3 *Life cycle costs of all insulation scenarios with different discount rates of evolutionary case 2*

Wall EPS thickness (mm)	Roof XPS thickness (mm)	LCC 5%	LCC 6%	LCC 7%	LCC 8%	LCC 9%	LCC 10%	LCC 11%	LCC 12%	LCC 13%	LCC 14%	LCC 15%
0	0	102903	93014	84639	77501	71379	66094	61507	57501	53983	50878	48123
25	25	86455	79355	73342	68217	63821	60027	56733	53857	51331	49102	47124
25	50	80912	74431	68942	64264	60251	56788	53782	51156	48851	46816	45011
25	75	78995	72785	67525	63043	59198	55879	52998	50482	48273	46323	44593
25	100	77912	71892	66794	62449	58722	55505	52713	50274	48133	46243	44566
25	150	78234	72356	67378	63136	59497	56356	53629	51248	49158	47312	45675
25	200	79043	73260	68363	64189	60609	57520	54837	52495	50438	48622	47011
50	25	82517	75885	70269	65482	61376	57832	54756	52069	49710	47628	45781
50	50	76758	70766	65692	61367	57657	54455	51676	49248	47117	45236	43566
50	75	74666	68962	64131	60013	56482	53434	50787	48476	46447	44656	43067
50	100	73527	68018	63354	59377	55967	53024	50468	48237	46278	44548	43013
50	150	73573	68233	63711	59857	56551	53697	51220	49057	47158	45481	43993
50	200	73988	68781	64372	60614	57390	54608	52192	50083	48231	46596	45146
75	25	80441	74099	68727	64149	60223	56834	53891	51322	49066	47075	45308
75	50	74524	68837	64021	59915	56394	53355	50717	48413	46390	44604	43020
75	75	72961	67511	62895	58961	55586	52673	50145	47937	45998	44287	42768
75	100	71782	66531	62085	58294	55044	52238	49802	47675	45807	44159	42696
75	150	72004	66905	62587	58906	55749	53024	50659	48593	46780	45178	43758
75	200	73109	68076	63815	60182	57067	54378	52043	50005	48215	46634	45233
100	25	79988	73779	68521	64039	60195	56877	53997	51482	49273	47324	45594
100	50	74984	69342	64565	60493	57000	53985	51368	49083	47076	45305	43733

Table A.3 *Life cycle costs of all insulation scenarios with different discount rates of evolutionary case 2 (continued)*

Wall EPS thickness (mm)	Roof XPS thickness (mm)	LCC 5%	LCC 6%	LCC 7%	LCC 8%	LCC 9%	LCC 10%	LCC 11%	LCC 12%	LCC 13%	LCC 14%	LCC 15%
100	75	72109	66831	62360	58550	55282	52461	50012	47874	45996	44339	42868
100	100	71291	66177	61847	58156	54990	52257	49885	47813	45994	44389	42964
100	150	71754	66769	62547	58949	55862	53199	50886	48866	47093	45528	44139
100	200	72384	67511	63385	59868	56851	54247	51986	50013	48279	46749	45392
150	25	80195	74147	69024	64658	60913	57680	54874	52424	50272	48373	46688
150	50	74491	69077	64492	60584	57232	54339	51827	49634	47708	46008	44499
150	75	72011	66922	62612	58938	55787	53067	50706	48645	46834	45236	43819
150	100	71901	66909	62681	59077	55986	53319	51003	48980	47205	45637	44246
150	150	71501	66720	62671	59220	56260	53706	51488	49551	47850	46349	45017
150	200	72615	67900	63907	60504	57584	55065	52878	50968	49291	47810	46497
200	25	81264	75292	70235	65925	62227	59036	56266	53847	51723	49848	48184
200	50	75338	70022	65520	61683	58392	55552	53086	50932	49042	47373	45892
200	75	73243	68215	63957	60328	57215	54528	52196	50159	48371	46792	45391
200	100	72684	67796	63657	60129	57103	54491	52224	50244	48505	46971	45609
200	150	72181	67515	63563	60195	57305	54812	52647	50757	49097	47632	46332
200	200	73578	68950	65032	61691	58826	56353	54206	52332	50686	49233	47944

Appendix B. Results of Sensitivity Test on Lifetime

Table B.1 *Life cycle costs of all insulation scenarios with different lifetimes*

	Thickness mm		Lifetime year				
Cases	Wall EPS	Roof XPS	20	25	30	35	40
Base case	0	0	21735	24580	26808	28554	29922
Base case	25	25	21370	22522	23424	24130	24684
Base case	25	50	20664	21606	22343	22921	23373
Base case	25	75	20801	21642	22301	22818	23222
Base case	25	100	21325	22117	22738	23224	23605
Base case	25	150	23111	23902	24521	25006	25386
Base case	25	200	24898	25687	26305	26789	27168
Base case	50	25	20161	21032	21714	22249	22668
Base case	50	50	20435	21224	21842	22326	22705
Base case	50	75	21326	22113	22730	23214	23592
Base case	50	100	22223	23010	23626	24109	24488
Base case	50	150	24021	24808	25425	25907	26286
Base case	50	200	25819	26606	27223	27705	28084
Base case	75	25	20487	21278	21897	22383	22763
Base case	75	50	21365	22153	22771	23254	23633
Base case	75	75	22262	23050	23667	24150	24529
Base case	75	100	23161	23948	24565	25048	25427
Base case	75	150	24959	25746	26363	26846	27225
Base case	75	200	26759	27546	28163	28646	29025
Base case	100	25	21417	22208	22827	23312	23691
Base case	100	50	22304	23092	23709	24193	24572
Base case	100	75	23204	23992	24609	25093	25472
Base case	100	100	24095	24882	25499	25982	26361
Base case	100	150	25895	26682	27299	27782	28161
Base case	100	200	27695	28482	29099	29582	29961
Base case	150	25	23287	24077	24696	25180	25560
Base case	150	50	24174	24962	25580	26063	26442
Base case	150	75	25074	25862	26480	26963	27342
Base case	150	100	25974	26762	27380	27863	28242
Base case	150	150	27774	28562	29180	29663	30042
Base case	150	200	29574	30362	30980	31463	31842
Base case	200	25	25156	25945	26564	27048	27428
Base case	200	50	26051	26840	27458	27942	28321

Table B.1 *Life cycle costs of all insulation scenarios with different lifetimes (continued)*

Cases	Thickness mm		Lifetime year			
	Wall EPS	Roof XPS	25	30	35	40
Base case	200	75	27734	28352	28835	29214
Base case	200	100	28642	29260	29744	30124
Base case	200	150	30442	31060	31544	31924
Base case	200	200	32242	32860	33344	33724
Evolutionary Case 1	0	0	47011	51273	54612	57227
Evolutionary Case 1	25	25	39420	41854	43761	45255
Evolutionary Case 1	25	50	37099	39241	40919	42233
Evolutionary Case 1	25	75	37043	39098	40708	41970
Evolutionary Case 1	25	100	37205	39194	40752	41972
Evolutionary Case 1	25	150	37973	39868	41353	42516
Evolutionary Case 1	25	200	39214	41059	42503	43635
Evolutionary Case 1	50	25	37495	39670	41373	42708
Evolutionary Case 1	50	50	34608	36439	37874	38998
Evolutionary Case 1	50	75	33929	35617	36940	37976
Evolutionary Case 1	50	100	34358	36003	37292	38302
Evolutionary Case 1	50	150	35309	36878	38106	39069
Evolutionary Case 1	50	200	36339	37838	39012	39932
Evolutionary Case 1	75	25	36697	38715	40295	41533
Evolutionary Case 1	75	50	33880	35560	36877	37908
Evolutionary Case 1	75	75	33266	34809	36018	36965
Evolutionary Case 1	75	100	33319	34786	35935	36835

Table B.1 *Life cycle costs of all insulation scenarios with different lifetimes (continued)*

	Thickness mm		Lifetime year			
	Wall	Roof				
Cases	EPS	XPS	25	30	35	40
Evolutionary Case 1	75	150	34382	35781	36878	37737
Evolutionary Case 1	75	200	35857	37228	38301	39142
Evolutionary Case 1	100	25	36784	38724	40244	41435
Evolutionary Case 1	100	50	33721	35302	36541	37511
Evolutionary Case 1	100	75	32833	34252	35364	36235
Evolutionary Case 1	100	100	33016	34370	35431	36262
Evolutionary Case 1	100	150	34281	35587	36610	37411
Evolutionary Case 1	100	200	35617	36881	37871	38646
Evolutionary Case 1	150	25	37965	39843	41314	42467
Evolutionary Case 1	150	50	34528	36012	37175	38087
Evolutionary Case 1	150	75	33825	35164	36213	37035
Evolutionary Case 1	150	100	33720	34968	35946	36712
Evolutionary Case 1	150	150	35053	36259	37203	37943
Evolutionary Case 1	150	200	36379	37542	38453	39166
Evolutionary Case 1	200	25	39198	41018	42444	43561
Evolutionary Case 1	200	50	35999	37447	38582	39471
Evolutionary Case 1	200	75	34770	36026	37009	37779
Evolutionary Case 1	200	100	34960	36151	37084	37815
Evolutionary Case 1	200	150	35993	37114	37993	38681
Evolutionary Case 1	200	200	37308	38385	39229	39890

Table B.1 *Life cycle costs of all insulation scenarios with different lifetimes (continued)*

Cases	Thickness mm Wall EPS	Roof XPS	Lifetime year 25	30	35	40
Evolutionary Case 2	0	0	94349	102903	109604	114853
Evolutionary Case 2	25	25	80313	86455	91266	95035
Evolutionary Case 2	25	50	75306	80912	85303	88744
Evolutionary Case 2	25	75	73623	78995	83203	86500
Evolutionary Case 2	25	100	72705	77912	81991	85186
Evolutionary Case 2	25	150	73150	78234	82217	85337
Evolutionary Case 2	25	200	74041	79043	82961	86031
Evolutionary Case 2	50	25	76781	82517	87011	90531
Evolutionary Case 2	50	50	71576	76758	80819	83999
Evolutionary Case 2	50	75	69732	74666	78531	81560
Evolutionary Case 2	50	100	68762	73527	77259	80183
Evolutionary Case 2	50	150	68954	73573	77192	80026
Evolutionary Case 2	50	200	69485	73988	77516	80280
Evolutionary Case 2	75	25	74955	80441	84739	88105
Evolutionary Case 2	75	50	69605	74524	78378	81397
Evolutionary Case 2	75	75	68247	72961	76655	79548
Evolutionary Case 2	75	100	67240	71782	75340	78127
Evolutionary Case 2	75	150	67594	72004	75459	78166
Evolutionary Case 2	75	200	68756	73109	76518	79190
Evolutionary Case 2	100	25	74617	79988	84195	87491

Table B.1 *Life cycle costs of all insulation scenarios with different lifetimes (continued)*

Cases	Thickness mm Wall EPS	Roof XPS	Lifetime year 25	30	35	40
Evolutionary Case 2	100	50	70104	74984	78807	81801
Evolutionary Case 2	100	75	67543	72109	75686	78489
Evolutionary Case 2	100	100	66868	71291	74756	77470
Evolutionary Case 2	100	150	67442	71754	75132	77778
Evolutionary Case 2	100	200	68169	72384	75686	78272
Evolutionary Case 2	150	25	74963	80195	84294	87505
Evolutionary Case 2	150	50	69808	74491	78160	81034
Evolutionary Case 2	150	75	67609	72011	75460	78161
Evolutionary Case 2	150	100	67583	71901	75284	77934
Evolutionary Case 2	150	150	67366	71501	74740	77278
Evolutionary Case 2	150	200	68537	72615	75810	78313
Evolutionary Case 2	200	25	76099	81264	85311	88481
Evolutionary Case 2	200	50	70740	75338	78940	81761
Evolutionary Case 2	200	75	68894	73243	76650	79319
Evolutionary Case 2	200	100	68457	72684	75996	78591
Evolutionary Case 2	200	150	68145	72181	75343	77820
Evolutionary Case 2	200	200	69575	73578	76714	79170

Appendix C. Results of Sensitivity Test on Energy Price

Table C.1 *Life cycle costs of all insulation scenarios with different energy price escalation rates*

Cases	Wall EPS thickness (mm)	Roof XPS thickness (mm)	Energy price escalation rates %			
			1	2	3	4
Base case	0	0	28585	32173	36421	41465
Base case	25	25	24143	25595	27315	29356
Base case	25	50	22931	24118	25524	27193
Base case	25	75	22827	23888	25144	26636
Base case	25	100	23233	24232	25415	26820
Base case	25	150	25014	26012	27192	28593
Base case	25	200	26797	27792	28970	30369
Base case	50	25	22258	23357	24657	26201
Base case	50	50	22334	23329	24507	25906
Base case	50	75	23222	24216	25392	26788
Base case	50	100	24118	25111	26286	27682
Base case	50	150	25916	26909	28084	29479
Base case	50	200	27714	28706	29881	31276
Base case	75	25	22391	23389	24570	25972
Base case	75	50	23263	24257	25434	26831
Base case	75	75	24159	25152	26329	27725
Base case	75	100	25057	26050	27226	28622
Base case	75	150	26855	27848	29023	30419
Base case	75	200	28655	29648	30823	32219
Base case	100	25	23320	24317	25497	26898
Base case	100	50	24202	25196	26373	27771
Base case	100	75	25102	26096	27273	28671
Base case	100	100	25991	26984	28159	29555
Base case	100	150	27791	28784	29959	31355
Base case	100	200	29591	30584	31759	33155
Base case	150	25	25189	26185	27365	28765
Base case	150	50	26072	27066	28243	29640
Base case	150	75	26972	27966	29143	30540
Base case	150	100	27872	28866	30043	31440
Base case	150	150	29672	30666	31843	33240
Base case	150	200	31472	32466	33643	35040
Base case	200	25	27057	28053	29231	30631
Base case	200	50	27951	28946	30124	31522

Table C.1 *Life cycle costs of all insulation scenarios with different energy price escalation rates (continued)*

Cases	Wall EPS thickness (mm)	Roof XPS thickness (mm)	Energy price escalation rates %			
			1	2	3	4
Base case	200	75	28844	29838	31015	32412
Base case	200	100	29753	30748	31926	33325
Base case	200	150	31553	32548	33726	35125
Base case	200	200	33353	34348	35526	36925
Evolutionary Case 1	0	0	54670	61533	69657	79304
Evolutionary Case 1	25	25	43794	47714	52353	57863
Evolutionary Case 1	25	50	40948	44397	48480	53329
Evolutionary Case 1	25	75	40737	44046	47964	52616
Evolutionary Case 1	25	100	40779	43981	47771	52272
Evolutionary Case 1	25	150	41379	44430	48042	52331
Evolutionary Case 1	25	200	42529	45499	49014	53188
Evolutionary Case 1	50	25	41403	44905	49050	53973
Evolutionary Case 1	50	50	37899	40848	44339	48484
Evolutionary Case 1	50	75	36963	39681	42899	46720
Evolutionary Case 1	50	100	37315	39965	43101	46826
Evolutionary Case 1	50	150	38128	40654	43643	47194
Evolutionary Case 1	50	200	39033	41446	44303	47695
Evolutionary Case 1	75	25	40323	43572	47417	51984
Evolutionary Case 1	75	50	36900	39606	42809	46613

Table C.1 *Life cycle costs of all insulation scenarios with different energy price escalation rates (continued)*

Cases	Wall EPS thickness (mm)	Roof XPS thickness (mm)	Energy price escalation rates %			
			1	2	3	4
Evolutionary Case 1	75	75	36039	38524	41466	44959
Evolutionary Case 1	75	100	35955	38316	41111	44431
Evolutionary Case 1	75	150	36897	39151	41818	44986
Evolutionary Case 1	75	200	38320	40526	43138	46239
Evolutionary Case 1	100	25	40271	43396	47094	51487
Evolutionary Case 1	100	50	36562	39108	42122	45701
Evolutionary Case 1	100	75	35383	37669	40373	43586
Evolutionary Case 1	100	100	35449	37630	40210	43276
Evolutionary Case 1	100	150	36628	38730	41219	44174
Evolutionary Case 1	100	200	37888	39923	42331	45191
Evolutionary Case 1	150	25	41340	44364	47943	52194
Evolutionary Case 1	150	50	37196	39586	42416	45777
Evolutionary Case 1	150	75	36232	38388	40941	43973
Evolutionary Case 1	150	100	35963	37973	40352	43177
Evolutionary Case 1	150	150	37220	39162	41460	44190
Evolutionary Case 1	150	200	38469	40341	42558	45190
Evolutionary Case 1	200	25	42469	45400	48868	52988

Table C.1 *Life cycle costs of all insulation scenarios with different energy price escalation rates (continued)*

Cases	Wall EPS thickness (mm)	Roof XPS thickness (mm)	Energy price escalation rates %			
			1	2	3	4
Evolutionary Case 1	200	50	38602	40934	43694	46973
Evolutionary Case 1	200	75	37027	39048	41441	44283
Evolutionary Case 1	200	100	37095	39012	41281	43976
Evolutionary Case 1	200	150	38008	39814	41951	44489
Evolutionary Case 1	200	200	39244	40979	43032	45471
Evolutionary Case 2	0	0	109721	123495	139799	159160
Evolutionary Case 2	25	25	91351	101240	112946	126847
Evolutionary Case 2	25	50	85380	94407	105092	117782
Evolutionary Case 2	25	75	83277	91927	102166	114325
Evolutionary Case 2	25	100	82062	90447	100371	112157
Evolutionary Case 2	25	150	82286	90473	100163	111671
Evolutionary Case 2	25	200	83030	91084	100617	111939
Evolutionary Case 2	50	25	87090	96327	107260	120245
Evolutionary Case 2	50	50	80890	89236	99114	110846
Evolutionary Case 2	50	75	78597	86542	95946	107114
Evolutionary Case 2	50	100	77325	84997	94078	104863
Evolutionary Case 2	50	150	77255	84693	93496	103951

Table C.1 *Life cycle costs of all insulation scenarios with different energy price escalation rates (continued)*

Cases	Wall EPS thickness (mm)	Roof XPS thickness (mm)	Energy price escalation rates %			
			1	2	3	4
Evolutionary Case 2	50	200	77578	84830	93415	103609
Evolutionary Case 2	75	25	84814	93648	104104	116522
Evolutionary Case 2	75	50	78446	86367	95743	106879
Evolutionary Case 2	75	75	76720	84311	93298	103969
Evolutionary Case 2	75	100	75402	82716	91372	101653
Evolutionary Case 2	75	150	75520	82622	91029	101013
Evolutionary Case 2	75	200	76578	83587	91884	101737
Evolutionary Case 2	100	25	84269	92917	103153	115309
Evolutionary Case 2	100	50	78874	86731	96032	107078
Evolutionary Case 2	100	75	75749	83102	91804	102140
Evolutionary Case 2	100	100	74817	81939	90369	100381
Evolutionary Case 2	100	150	75191	82135	90354	100114
Evolutionary Case 2	100	200	75744	82530	90564	100104
Evolutionary Case 2	150	25	84366	92791	102764	114607
Evolutionary Case 2	150	50	78224	85765	94692	105292
Evolutionary Case 2	150	75	75520	82609	91000	100964
Evolutionary Case 2	150	100	75343	82297	90527	100302

Table C.1 *Life cycle costs of all insulation scenarios with different energy price escalation rates (continued)*

Cases	Wall EPS thickness (mm)	Roof XPS thickness (mm)	Energy price escalation rates %			
			1	2	3	4
Evolutionary Case 2	150	150	74797	81456	89338	98699
Evolutionary Case 2	150	200	75866	82433	90207	99438
Evolutionary Case 2	200	25	85382	93699	103544	115237
Evolutionary Case 2	200	50	79003	86407	95170	105578
Evolutionary Case 2	200	75	76710	83713	92002	101846
Evolutionary Case 2	200	100	76054	82862	90920	100490
Evolutionary Case 2	200	150	75398	81898	89591	98727
Evolutionary Case 2	200	200	76769	83214	90844	99904

Appendix D. HVAC System Input in EnergyPlus

The following scripts are the text input for the HVAC system in EnerygPlus:

```
!-   ===========  ALL OBJECTS IN CLASS:
HVACTEMPLATE:THERMOSTAT ===========

HVACTemplate:Thermostat,

    All Zones,               !- Name

    Hg-SetP-Sch 18,          !- Heating Setpoint Schedule Name

    ,                        !- Constant Heating Setpoint {C}

    Cl-SetP-Sch 23,          !- Cooling Setpoint Schedule Name

    ;                        !- Constant Cooling Setpoint {C}

!-   ===========  ALL OBJECTS IN CLASS:
HVACTEMPLATE:ZONE:VAV ===========

HVACTemplate:Zone:VAV,

    ZONE ONE,                !- Zone Name

    VAV Sys 1,               !- Template VAV System Name

    All Zones,               !- Template Thermostat Name

    autosize,                !- Supply Air Maximum Flow Rate {m3/s}

    ,                        !- Zone Heating Sizing Factor

    ,                        !- Zone Cooling Sizing Factor

    Constant,                !- Zone Minimum Air Flow Input Method

    0.3,                     !- Constant Minimum Air Flow Fraction
```

```
,                    !- Fixed Minimum Air Flow Rate {m3/s}
,                    !- Minimum Air Flow Fraction Schedule Name
flow/person,         !- Outdoor Air Method
0.00944,             !- Outdoor Air Flow Rate per Person {m3/s}
0.0,                 !- Outdoor Air Flow Rate per Zone Floor Area {m3/s-m2}
0.0,                 !- Outdoor Air Flow Rate per Zone {m3/s}
HotWater,            !- Reheat Coil Type
,                    !- Reheat Coil Availability Schedule Name
Reverse,             !- Damper Heating Action
,                    !- Maximum Flow per Zone Floor Area During Reheat {m3/s-m2}
,                    !- Maximum Flow Fraction During Reheat
,                    !- Maximum Reheat Air Temperature {C}
,                    !- Design Specification Outdoor Air Object Name
,                    !- Supply Plenum Name
,                    !- Return Plenum Name
None,                !- Baseboard Heating Type
,                    !- Baseboard Heating Availability Schedule Name
autosize;            !- Baseboard Heating Capacity {W}
```

```
!-   ===========  ALL OBJECTS IN CLASS:
HVACTEMPLATE:SYSTEM:VAV ===========

HVACTemplate:System:VAV,
    VAV Sys 1,               !- Name
    FanAvailSched,           !- System Availability Schedule Name
    autosize,                !- Supply Fan Maximum Flow Rate {m3/s}
    autosize,                !- Supply Fan Minimum Flow Rate {m3/s}
    0.7,                     !- Supply Fan Total Efficiency
    500,                     !- Supply Fan Delta Pressure {Pa}
    0.9,                     !- Supply Fan Motor Efficiency
    1,                       !- Supply Fan Motor in Air Stream Fraction
    ChilledWater,            !- Cooling Coil Type
    ,                        !- Cooling Coil Availability Schedule Name
    ,                        !- Cooling Coil Setpoint Schedule Name
    12.8,                    !- Cooling Coil Design Setpoint {C}
    HotWater,                !- Heating Coil Type
    ,                        !- Heating Coil Availability Schedule Name
    ,                        !- Heating Coil Setpoint Schedule Name
    10,                      !- Heating Coil Design Setpoint {C}
    0.8,                     !- Gas Heating Coil Efficiency
    0.0,                     !- Gas Heating Coil Parasitic Electric Load {W}
```

```
None,                    !- Preheat Coil Type
,                        !- Preheat Coil Availability Schedule Name
,                        !- Preheat Coil Setpoint Schedule Name
,                        !- Preheat Coil Design Setpoint {C}
0.8,                     !- Gas Preheat Coil Efficiency
0.0,                     !- Gas Preheat Coil Parasitic Electric Load {W}
autosize,                !- Maximum Outdoor Air Flow Rate {m3/s}
autosize,                !- Minimum Outdoor Air Flow Rate {m3/s}
FixedMinimum,            !- Minimum Outdoor Air Control Type
Min OA Sched,            !- Minimum Outdoor Air Schedule Name
DifferentialDryBulb,     !- Economizer Type
NoLockout,               !- Economizer Lockout
19,                      !- Economizer Upper Temperature Limit {C}
4,                       !- Economizer Lower Temperature Limit {C}
,                        !- Economizer Upper Enthalpy Limit {J/kg}
,                        !- Supply Plenum Name
Plenum,                  !- Return Plenum Name
DrawThrough,             !- Supply Fan Placement
InletVaneDampers,        !- Supply Fan Part-Load Power Coefficients
CycleOnAny,              !- Night Cycle Control
,                        !- Night Cycle Control Zone Name
```

```
    None,                  !- Heat Recovery Type
    0.70,                  !- Sensible Heat Recovery Effectiveness
    0.65,                  !- Latent Heat Recovery Effectiveness
    None,                  !- Cooling Coil Setpoint Reset Type
    None,                  !- Heating Coil Setpoint Reset Type
    CoolReheat,            !- Dehumidification Control Type
    ZONE ONE,              !- Dehumidification Control Zone Name
    50,                    !- Dehumidification Setpoint {percent}
    ElectricSteam,         !- Humidifier Type
    FanAvailSched,         !- Humidifier Availability Schedule Name
    0.000001,              !- Humidifier Rated Capacity {m3/s}
    2690.0,                !- Humidifier Rated Electric Power {W}
    ZONE ONE,              !- Humidifier Control Zone Name
    40;                    !- Humidifier Setpoint {percent}

!-   ===========  ALL OBJECTS IN CLASS:
HVACTEMPLATE:PLANT:CHILLEDWATERLOOP ===========


  HVACTemplate:Plant:ChilledWaterLoop,
    Chilled Water Loop,    !- Name
    ,                      !- Pump Schedule Name
    INTERMITTENT,          !- Pump Control Type
```

```
Default,                !- Chiller Plant Operation Scheme Type
,                       !- Chiller Plant Equipment Operation Schemes Name
,                       !- Chilled Water Setpoint Schedule Name
7.22,                   !- Chilled Water Design Setpoint {C}
VariablePrimaryNoSecondary,  !- Chilled Water Pump Configuration
90000,                  !- Primary Chilled Water Pump Rated Head {Pa}
179352,                 !- Secondary Chilled Water Pump Rated Head {Pa}
Default,                !- Condenser Plant Operation Scheme Type
,                       !- Condenser Equipment Operation Schemes Name
,                       !- Condenser Water Temperature Control Type
,                       !- Condenser Water Setpoint Schedule Name
29.4,                   !- Condenser Water Design Setpoint {C}
179352,                 !- Condenser Water Pump Rated Head {Pa}
None,                   !- Chilled Water Setpoint Reset Type
12.2,                   !- Chilled Water Setpoint at Outdoor Dry-Bulb Low {C}
15.6,                   !- Chilled Water Reset Outdoor Dry-Bulb Low {C}
6.7,                    !- Chilled Water Setpoint at Outdoor Dry-Bulb High {C}
26.7;                   !- Chilled Water Reset Outdoor Dry-Bulb High {C}

!-   ===========  ALL OBJECTS IN CLASS: HVACTEMPLATE:PLANT:CHILLER ===========

HVACTemplate:Plant:Chiller,
```

```
    Main Chiller,            !- Name
    ElectricReciprocatingChiller,  !- Chiller Type
    autosize,                !- Capacity {W}
    3.2,                     !- Nominal COP {W/W}
    WaterCooled,             !- Condenser Type
    1,                       !- Priority
    ;                        !- Sizing Factor

!-   ===========  ALL OBJECTS IN CLASS: HVACTEMPLATE:PLANT:TOWER ===========

HVACTemplate:Plant:Tower,
    Main Tower,              !- Name
    SingleSpeed,             !- Tower Type
    autosize,                !- High Speed Nominal Capacity {W}
    autosize,                !- High Speed Fan Power {W}
    autosize,                !- Low Speed Nominal Capacity {W}
    autosize,                !- Low Speed Fan Power {W}
    autosize,                !- Free Convection Capacity {W}
    1,                       !- Priority
    ;                        !- Sizing Factor
```

!- =========== ALL OBJECTS IN CLASS: HVACTEMPLATE:PLANT:HOTWATERLOOP ===========

HVACTemplate:Plant:HotWaterLoop,

Hot Water Loop, !- Name

, !- Pump Schedule Name

INTERMITTENT, !- Pump Control Type

Default, !- Hot Water Plant Operation Scheme Type

, !- Hot Water Plant Equipment Operation Schemes Name

, !- Hot Water Setpoint Schedule Name

82, !- Hot Water Design Setpoint {C}

VariableFlow, !- Hot Water Pump Configuration

90000, !- Hot Water Pump Rated Head {Pa}

OutdoorAirTemperatureReset, !- Hot Water Setpoint Reset Type

82.2, !- Hot Water Setpoint at Outdoor Dry-Bulb Low {C}

-6.7, !- Hot Water Reset Outdoor Dry-Bulb Low {C}

65.6, !- Hot Water Setpoint at Outdoor Dry-Bulb High {C}

10; !- Hot Water Reset Outdoor Dry-Bulb High {C}

!- =========== ALL OBJECTS IN CLASS: HVACTEMPLATE:PLANT:BOILER ===========

HVACTemplate:Plant:Boiler,

```
    Main Boiler,            !- Name
    HotWaterBoiler,         !- Boiler Type
    autosize,               !- Capacity {W}
    0.68,                   !- Efficiency
    Coal,                   !- Fuel Type
    1,                      !- Priority
    ;                       !- Sizing Factor
  !-   ===========  ALL OBJECTS IN CLASS: SIZING:PARAMETERS
===========
  Sizing:Parameters,
    1.2,                    !- Heating Sizing Factor
    1.2;                    !- Cooling Sizing Factor
```