博士論文

Environmental Evaluations and Cost Performance of Prefabricated Buildings Based on the Life Cycle Assessment

ライフサイクルアセスメント(LCA) に基づくプレハブ建築の環境評価及びコストパフォーマンスに関する研究

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Environmental Evaluations and Cost Performance of Prefabricated Buildings Based on the Life Cycle Assessment

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Preface

This thesis research was performed at the Department of Architecture at the University of Kitakyushu. This thesis presents a study which combines insights from the prefabricated building field of policy, technology, energy, environmental studies. The focus is set on environmental and cost performance of prefabricated building based on life cycle assessment.

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Environmental and Cost Performance of Prefabricated Buildings Based on the Life Cycle Assessment

Abstract

The prefabricated building has been developed for more than 100 years. It has made great achievements and become the future development direction of the construction industry. But it still faces many obstacles and challenges. As a mature evaluation theory, life cycle assessment method is currently widely used in the field of architecture. This article summarizes the development of prefabricated buildings in various countries. Combined with the historical economic background of the respective countries where the prefabricated buildings are located, the development ideas and technical characteristics of prefabricated buildings in various countries are analyzed. The purpose is to understand the concept of prefabricated buildings and provide references for the development of prefabricated buildings in other countries. By summarizing and combing the existing life cycle assessment methods, to understand the concept and method of the life cycle assessment method and construct a life cycle assessment method suitable for evaluating prefabricated buildings. The assessment of the environmental impact of a building throughout its life cycle is a necessary means to achieve targeted energy conservation and emission reduction. The study divides the life cycle of prefabricated buildings into design stage, materialization stage, use and maintenance stage, and dismantling and recycling stage. Accounted for each stage separately, to determine the impact of prefabricated buildings on the environment throughout the life cycle. The article also conducted a comparative study on prefabricated buildings and traditional buildings and analyzed the environmental impact and cost performance of the two from the perspective of the building life cycle. In addition, from the perspective of building life cycle, the optimal solution of insulation thickness of building envelope structure in different regions is analyzed. The conclusions of this research are summarized as follows.

In Chapter one, Background and Purpose of This Study， introduced today's global issues, such as climate change, greenhouse gas emissions, population growth and accelerated urbanization, which poses great challenges to the sustainable development of human society. Among the various causes of these problems, the construction industry has been criticized as a major developer of major energy and natural resources. The global construction sector consumes 40% of the total final energy use. Buildings that account for upstream power generation account for 36% of global energy-related carbon dioxide emissions. In order to solve these problems, prefabricated construction has become the development direction of the construction industry. Prefabricated buildings are a widely accepted method used to replace traditional on-site construction methods. The advantages of prefabricated buildings are saving time, improving quality, reducing waste and reducing energy consumption. In order to clarify the impact on the environment during the entire life cycle of the prefabricated building, a life cycle analysis method is proposed to evaluate its impact on the environment.

In Chapter two, Survey on the Prefabricated Buildings Development in Various Countries, provided a comprehensive survey of the historical and current development of prefabricated buildings in different countries. Through comparative research on the development history of prefabricated buildings in different countries, it is found that the development of prefabricated buildings in various countries is based on the increase in housing demand and large-scale housing construction. Under the encouragement and guidance of government policies, research institutions and enterprises promote the development of prefabricated buildings. The prefabricated buildings in various countries has experienced almost half a century of development and has basically reached a mature and stable period. Prefabricated buildings have become one of the main methods of housing construction in developed countries.

In Chapter three, Theories and Methodology of the Study, investigated and analyzed the life cycle assessment methods, the definition of life cycle analysis methods is clarified, and the advantages and disadvantages of different methods are analyzed. At the same time, according to the characteristics of prefabricated buildings, build a life cycle model that conforms to the characteristics of prefabricated buildings. The simulation models are detailed introduce in this chapter as well. The climate data in this study are mainly employed TMY3 files which are derive from Integrated Surface Database (ISD) of US National Oceanic and Atmospheric Administrations (NOAA) with hourly data through 2017.The building energy consumption simulation among the 7 stations in Japan were estimated using EnergyPlus, a validated and physics-based BES program developed by the U.S. Department of Energy (DOE).

In Chapter four, Environmental and Cost Performance Comparison between Prefabricated and Traditional Buildings, assess the environmental impact of prefabricated buildings and traditional cast-in-situ buildings over the building life cycle using a hybrid model. A case study of a building with a 40% assembly rate in Japan was employed for evaluation. The comparative analysis of the environmental and environmental impacts and cost differences of the two buildings during their entire life cycle, as well as the impact of different assembly rates and precast pile foundations on the environment. It concluded that the total energy consumption, and carbon emissions of the prefabricated building was 7.54%, and 7.17%, respectively, less than that of the traditional cast-in-situ building throughout the whole life cycle. The carbon emissions reduction in the operation phase reached a peak of 4.05 kg CO2/year·m2. The prefabricated building was found to cost less than the traditional cast-in-situ building, reducing the price per square meter by 10.62%. The prefabricated building has advantages in terms of reducing global warming, acid rain, and health damage by 15% reduction. With the addition of the assembly rate, the carbon emissions and cost dropped, bottoming out when the assembly rate was 60%. After that, an upward trend was shown with the assembly rate increasing. Additionally, this study outlined that the prefabricated pile foundations is not applicable due to its high construction cost and environmental impact.

In Chapter five, Environmental Performance of Envelope Insulation in Prefabricated Building, proposed models for the thermal insulation system of prefabricated buildings and traditional cast-in-situ buildings, according to the characteristics of the two buildings at different stages. The process analysis method is used to compare the environmental impacts of the two building thermal insulation systems during their life cycle, and to provide references for the development of effective emission reduction measures for carbon emission levels at different stages.

In Chapter six, Regional Applicability and Cost Performance of Envelope Insulation in Prefabricated Buildings, the energy consumption of the insulation materials in the production process and the reduction of the energy consumption of the air conditioner by increasing the thickness of the insulation layer are comprehensively considered according to the division of the life cycle of the insulation system in Chapter 5. Based on different thermal climate zones in Japan, the relationship between the thickness of the insulation material in each zone and the energy consumption of the air conditioning was analyzed. The study found that the thickness of the insulation layer will reduce the energy-saving effect of the building when it exceeds a certain value. The optimal insulation layer thickness for different thermal engineering zones is given.

In Chapter seven, the whole summary of each chapter has been presented.

Keywords: Prefabricated building; life cycle assessment; environment impact; thermal insulation

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Preface

Acknowledgements

Abstract

Chapter 1. Background and Purpose of This Study

1.1. Research Background

1.1.1.Climate change and building energy consumption

Since the Industrial Revolution, global temperatures have been rising. The main reason lies in human activities and some changes in nature. A lot of evidence shows that the main reason is due to human activities. As of 2019, the global temperature is at the highest stage in history (Figure 1.1, Figure 1.2 and Figure 1.3 [1]. Since 1880, the global average temperature has increased by 1 ° C and the average annual increase by 0.15-0.20 ° C. Arctic glaciers have fallen by 12.85% per decade, and Antarctic glaciers have fallen by 127 Gt / year (margin: ± 39) [2]. The annual report of the Intergovernmental Panel on Climate Change (IPCC) pointed out that as global energy consumption continues to increase and population increases, the concentration of greenhouse gases will soon exceed the acceptable limit of the natural environment [3].

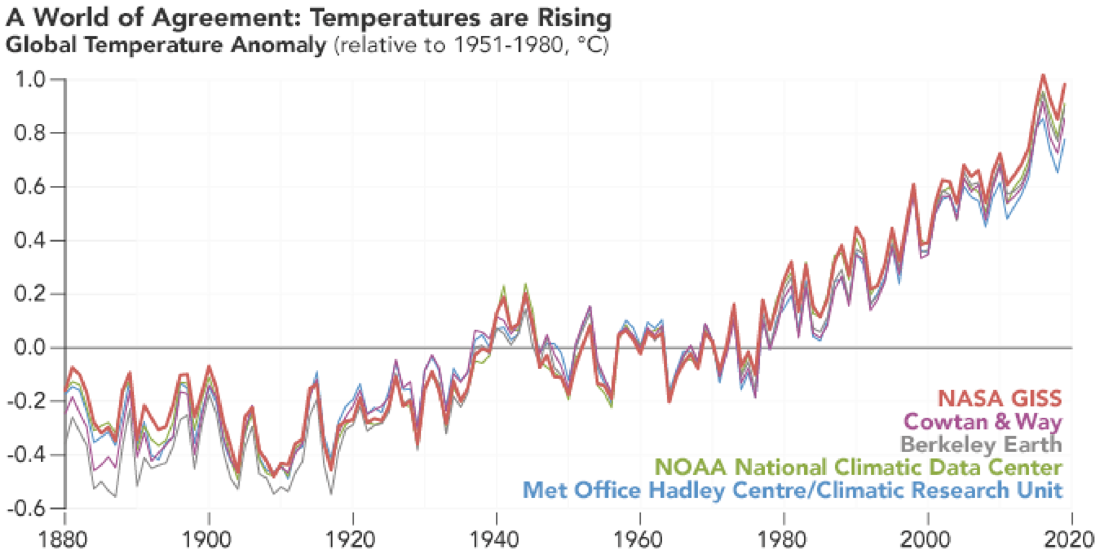

Figure 1.1. Global temperature changes from 1880 to 2020 [1]

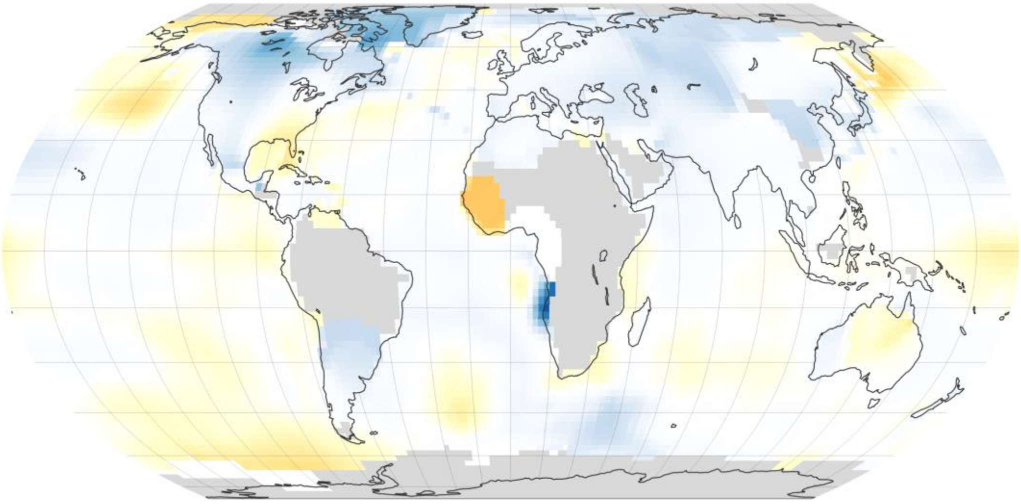

Figure 1.2.Earth surface temperature changes from 1880 to 1884 [1]

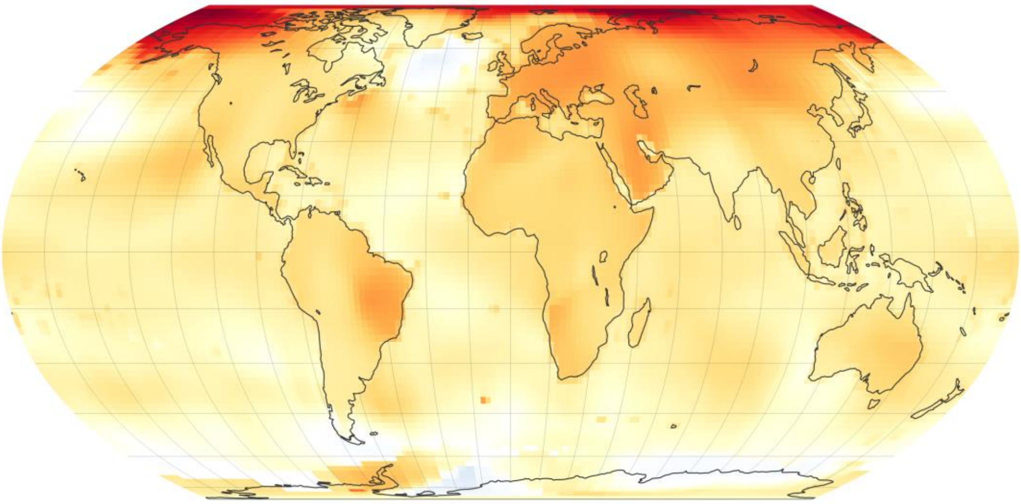

Figure 1.3. Earth surface temperature changes from 2015 to 2019 [1]

According to the report of the Intergovernmental Panel on Climate Change (IPCC), 40% of global energy consumption and 36% of carbon dioxide emissions originate from construction-related activities [4]. The United Nations Environment Program (UNEP) announced that with the rapid development of urbanization and the inefficiency of existing building stocks, unless mitigation measures are taken, greenhouse gas emissions will more than double in the next 20 years [5]. Therefore, reducing greenhouse gas emissions in the construction sector is the focus of the future.

1.1.2.Population growth and urbanization

Research shows that although the world population growth trend is gradually slowing, the world population is still growing. By 2100, the global population is expected to exceed 10 billion [6] . The growing population and the acceleration of the urbanization process in the world have led to an increase in the urban population year by year. Compared with 1950, the percentage of urbanized population in 2018 increased by 24% [7]. The United Nations report shows that the population of urban areas will grow year by year at a rate of 0.898%. It is expected that by 2050, the proportion of the world ’s urban population will exceed 68% [7]. The development of urbanization and the growth of urban population will inevitably lead to the growth of urban construction area. Studies have shown that compared with 2013, the world's housing area will increase by 60 billion cubic meters in 2020 [8] . With the continuous growth of construction area, the construction industry has gradually increased the consumption of materials and energy. The energy consumption and waste of the building during the operation phase have also increased, which has increased the burden on the environment. Taking China as an example, as the world's second largest economy and the most populous country, China's urbanization process has been increasing year by year at a rate of 0.8%, with an annual construction area of 1.8 billion cubic meters [9]. With the economic development, the increase in energy consumption in the construction industry and the increase in construction waste year by year have aggravated the negative impact of the environment. Studies have shown that the mortality rate of urban populations due to respiratory diseases has increased from 0.65‰in 2009 to 0.74‰ in 2018 [9]. Therefore, how to reduce the energy consumption and environmental impact of the construction industry is particularly important and urgent.

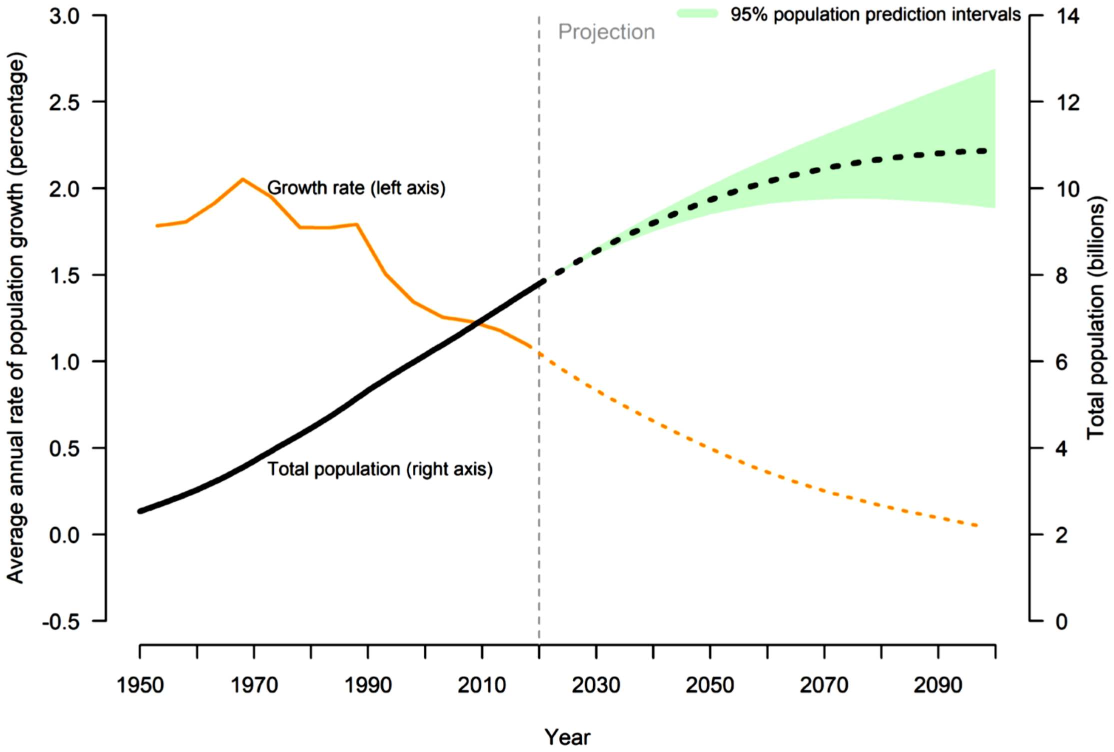

Figure 1.4.Population growth tendency [10]

1.1.3.Problems in the construction sector

Increased greenhouse gas content is one of the main causes of global warming. Controlling the concentration of greenhouse gases is the main method to slow down global warming. Direct consumption of energy (gasoline, diesel and kerosene consumed by machinery, oil and natural gas consumed by heating, etc.) and indirect consumption (energy consumed by power generation) are the main activities that generate greenhouse gas emissions. The World Watch Institute pointed out in its survey report that the urban area accounts for only 2% of the total land area, but its greenhouse gas emissions account for more than 70% of the total emissions, 60% of household water consumption and 76% of total wood consumption. The expansion of the city and the growth of the population will definitely increase energy consumption, consume more resources, and generate more garbage, which will aggravate the destruction of the environment and negatively affect the environment. The waste generated during the construction process has a great impact on the environment. Related studies indicate that the construction process accounts for 32% of energy consumption, 30% of carbon dioxide emissions and 30-40% of waste production [11]. The construction waste generated during the demolition process is usually composed of stucco, concrete, rubber, block, asphalt, and chemical substances, accounting for approximately 10–30% of all landfill waste [12]. However, it is reported that construction waste in Chicago (United States) accounts for about 60% of all waste, in the UK it is 50% and in Hong Kong it is 37% [13]. Figure 1.5 and Figure 1.6 show the environmental impact of construction-related activities.

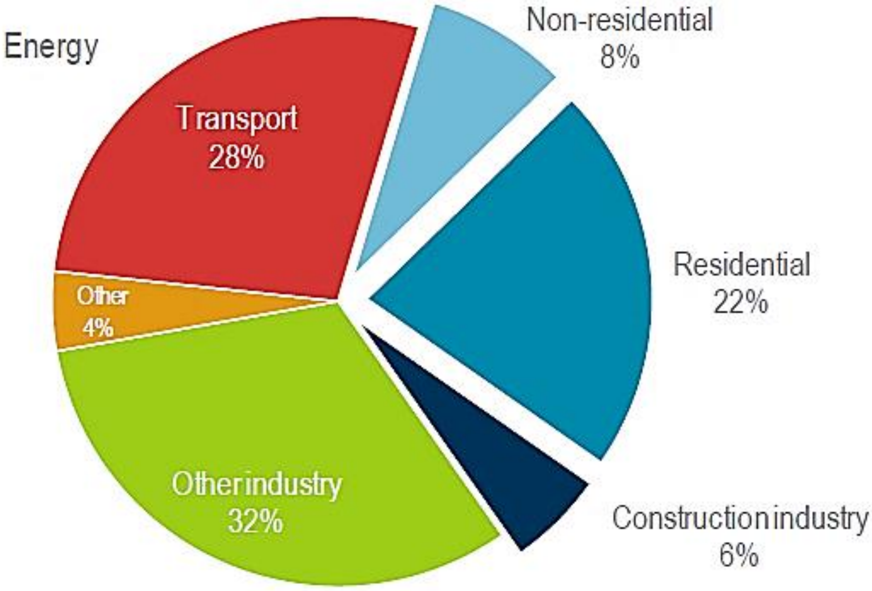

Figure 1.5. Share of global final energy consumption by sector [14]

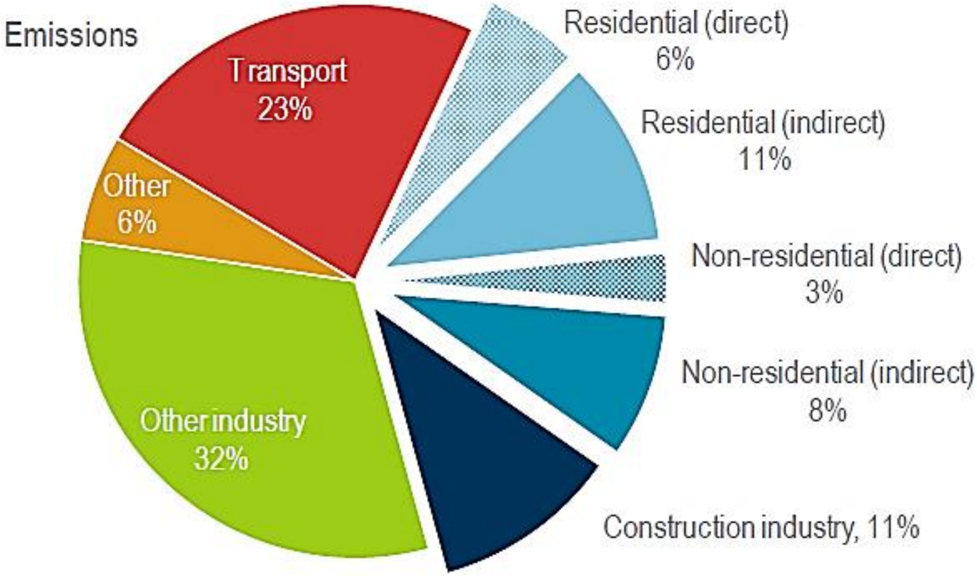

Figure 1.6. Share of global energy-related CO_2 emissions by sector [14]

In order to solve these problems, prefabricated construction has become the development direction of the construction industry. Prefabricated building is a widely accepted method to replace the traditional on-site construction method [15]. The advantages of prefabricated buildings are time saving, quality improvement, waste reduction and energy consumption reduction [15–17]. The application of prefabricated buildings has developed rapidly around the world. For example, in early 1996, the prefabrication levels in Germany, the Netherlands and Denmark rose to 31%, 40% and 43%, respectively [18]. The size of the UK prefabricated construction industry has increased from £ 2.2 billion in 2004 to £ 6 billion in 2006.

However, today's prefabricated buildings still face many challenges. Some studies have shown that the understanding of prefabricated buildings is particularly important in the initial application of prefabricated buildings [19]. Studies have pointed out that the obstacles to the development of prefabricated buildings are mainly the lack of knowledge about prefabricated buildings, and the lack of reasonable planning for the production and project planning of prefabricated components, resulting in cost and technical problems [20]. The lack of knowledge refers to the lack of understanding of the prefabricated building concept into the practical application of people, including owners, architects, construction engineers, construction managers, construction operators and other stakeholders. The significance of knowledge is concentrated in three main areas: the advantages of prefabricated buildings, the types of existing prefabricated buildings, and the understanding of how to use prefabricated building technologies correctly and effectively. In addition, prefabricated buildings also have certain requirements for sites and roads. Due to the particularity of assembled components, it needs to be produced in a prefabricated factory. In order to reduce the cost of the project, this requires that the distance between the project and the prefabrication plant should not be too far. In addition, the transportation of prefabricated components may also have a certain impact on urban traffic. Therefore, the road conditions around the construction site should meet the transportation of components [21].

At present, most assessments of prefabricated buildings focus on the construction stage of the building, while ignoring the impact of the material production stage, use stage and disassembly stage on the environment. Therefore, an appropriate evaluation model should be constructed to evaluate the energy consumption and environmental load of the prefabricated building from the perspective of its full life cycle [21]. In addition, for air conditioning energy saving, current research often only focuses on buildings to reduce the heating and cooling load of air conditioning through technical means, so as to achieve energy saving and emission reduction. However, the energy saving of buildings should be considered from the perspective of the entire life cycle, that is, the energy consumption increased by the application of energy-saving technologies should be taken into consideration, and then whether the purpose of energy saving is achieved in the entire life cycle of the building should be evaluated.

1.2.Purpose and Significance of This Study

1.2.1. Purpose of This Study

Prefabricated buildings have been developed for more than 100 years. It has made great achievements and serves as the future development direction of architecture, but still faces many obstacles and challenges. As a mature evaluation theory, life cycle assessment method is currently widely used in the field of architecture. With regard to prefabricated buildings, this article summarizes the development of prefabricated buildings in various countries. Combined with the historical and economic background of the respective countries where the prefabricated buildings are located, the development ideas and technical characteristics of prefabricated buildings in various countries are analyzed. The purpose is to understand the concept of prefabricated buildings and provide references for the development of prefabricated buildings in other countries. By summarizing and combing the existing life cycle assessment methods, understand the concept and evaluation method of the life cycle assessment method, and construct a life cycle assessment method suitable for evaluating prefabricated buildings. Evaluating the environmental impact of a building throughout its life cycle is a necessary means to achieve targeted energy conservation and emission reduction. By dividing the life cycle of the prefabricated building into the design stage, materialization stage, use and maintenance stage, and dismantling and recycling stage, the accounting is performed separately. The impact on the environment during the entire life cycle of the prefabricated building is determined. This study highlights the following goals:

Through the summary of the development process of prefabricated buildings in various countries, understand the meaning and motive of prefabricated buildings. In order to analyze the impact of prefabricated buildings on the environment, the existing life cycle assessment methods are summarized. And build a full life cycle model suitable for prefabricated buildings for prefabricated buildings. Through the comparison between prefabricated buildings and traditional cast-in-place buildings, it is clear that the stages of the whole life cycle of prefabricated buildings are different from traditional cast-in-place buildings. Through the research on the case of prefabricated pile expansion with different assembly rates and prefabricated pile foundations, the impact of the assembly rate and the application of precast pile foundations on the environment is analyzed.

By constructing the life cycle model of the prefabricated building insulation system, quantitative analysis of the energy consumption carbon emissions and energy consumption of each stage of the prefabricated building insulation system. Based on the above results, a thermal insulation thickness scheme suitable for different thermal climate zones in Japan was proposed: increasing the thickness of the thermal insulation layer can reduce the heating and cooling load of the building. However, the increased thermal insulation material also brings higher energy consumption investment in material production. Therefore, the actual energy-saving effect of a building can only be determined by incorporating the production of insulation materials into the building insulation system. By comparing the energy consumption of materials and the energy savings brought by increasing the thickness of the insulation layer, the reasonable thickness of the insulation layer in different thermal zones is determined.

1.2.2.Significance of This Study

With the continuous development of human industry, prefabricated buildings have different development motives and meanings in different periods. This article summarizes the development background and current situation of prefabricated buildings in different countries, analyzes the research results and development background of prefabricated buildings in different stages in various countries, and clarifies the definition of prefabricated buildings. Through the life cycle assessment method, construct a prefabricated building life cycle assessment model, analyzed the impact of each stage of the life cycle of prefabricated buildings on the environment based on a hybrid model. The application of the model was based on existing data to guarantee the integrity of the system boundary and the accuracy of the calculation results. In the case study, the influences of prefabricated buildings and traditional cast-in-situ buildings on the environment during the life cycle were compared. Moreover, the carbon emissions of prefabricated buildings with prefabricated pile foundations and different assembly rates were studied. Suggestions were made from the perspective of the application of prefabricated buildings and industry development.

With the continuous development of human industry, prefabricated buildings have different development motives and meanings in different periods. This article summarizes the development background and current situation of prefabricated buildings in different countries, analyzes the research results and development background of prefabricated buildings in different stages in various countries, and clarifies the definition of prefabricated buildings. At the same time, through the life cycle assessment method, construct a prefabricated building life cycle assessment model, analyze the impact of each stage of the life cycle of prefabricated buildings on the environment based on a hybrid model. The application of the model was based on existing data to guarantee the integrity of the system boundary and the accuracy of the calculation results. In the case study, the influences of prefabricated buildings and traditional cast-in-situ buildings on the environment during the life cycle were compared. Moreover, the carbon emissions of prefabricated buildings with prefabricated pile foundations and different assembly rates were studied. And made recommendations from the perspective of the application of prefabricated buildings and industry development.

Through the component prefabricated building insulation system model, the process analysis method is used to analyze the difference between the assembly building insulation system and the traditional cast-in-situ building insulation system. Through the simulated building energy consumption data and the energy consumption in the life cycle of the thermal insulation system, the reasonable thickness of the protective layer for different thermal climate zones in Japan is given.

1.3. Structure of This Study

In Chapter one, the development of prefabricated buildings background and current global issues related to building construction are reviewed. In addition, the purpose and structure of this research is proposed.

In Chapter two, provided a comprehensive survey of the historical and current development of prefabricated buildings in different countries. Through comparative research on the development history of prefabricated buildings in different countries, it is found that the development of prefabricated buildings in various countries is based on the increase in housing demand and large-scale housing construction. Under the encouragement and guidance of government policies, research institutions and enterprises promote the development of prefabricated buildings. The prefabricated buildings in various countries has experienced almost half a century of development and has basically reached a mature and stable period. Prefabricated buildings have become one of the main methods of housing construction in developed countries.

In Chapter three, introduced the research methodology and simulation theories. By sorting out different life cycle assessment methods, the definition of life cycle analysis methods is clarified, and the advantages and disadvantages of different methods are analyzed. At the same time, according to the characteristics of prefabricated buildings, build a life cycle model that conforms to the characteristics of prefabricated buildings. The simulation models are detailed introduce in this chapter as well. The climate data in this study are mainly employed TMY3 files which are derive from Integrated Surface Database (ISD) of US National Oceanic and Atmospheric Administrations (NOAA) with hourly data through 2017.The building energy consumption simulation among the 7 stations in Japan were estimated using EnergyPlus, a validated and physics-based BES program developed by the U.S. Department of Energy (DOE).

In Chapter four, assess the environmental impact of prefabricated buildings and traditional cast-in-situ buildings over the building life cycle using a hybrid model. A case study of a building with a 40% assembly rate in Japan was employed for evaluation. The comparative analysis of the environmental and environmental impacts and cost differences of the two buildings during their entire life cycle, as well as the impact of different assembly rates and precast pile foundations on the environment.

In Chapter five, according to the characteristics of the two buildings at different stages, the life cycle models of the thermal insulation system of prefabricated buildings and traditional cast-in-situ buildings are constructed. The process analysis method is used to compare the environmental impacts of the two building thermal insulation systems during their life cycle, and to provide references for the development of effective emission reduction measures for carbon emission levels at different stages.

In Chapter six, the energy-saving analysis of the prefabricated building insulation system for different Japanese thermal engineering zones is carried out. According to the division of the life cycle of the insulation system in Chapter five, the energy consumption of the insulation materials in the production process and the reduction of the energy consumption of the air conditioner by increasing the thickness of the insulation layer are comprehensively considered. Based on different thermal engineering zones, the relationship between the thickness of the insulation material in each zone and the energy consumption of the air conditioner was analyzed. Based on the above theory, it is found that the thickness of the insulation layer will reduce the energy-saving effect of the building after a certain value is exceeded, and the thickness of the insulation layer suitable for different thermal engineering zones is given.

In Chapter seven, the whole summary of each chapter has been presented.

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LITERATURE REVIEW	**CHAPTER TWO** Survey on the Prefabricated Buildings Development in Various Countries
THEORETICAL STUDY	**CHAPTER THREE** Theories and Methods of Life Cycle Assessment and Building Simulation
NUMERICAL ANALYSIS	**CHAPTER FOUR** Environmental and Cost Performance Comparison between Prefabricated and Traditional Buildings
	CHAPTER FIVE Environmental and Cost Performance Comparison of Envelope Insulation between Prefabricated and Traditional Buildings
	CHAPTER SIX Regional Applicability Performance of Envelope Insulation system in Prefabricated Buildings
CONCLUSION	**CHAPTER SEVEN** Conclusions

Figure 1.7. Research Flow

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Chapter 2. Survey on the Prefabricated Buildings Development in Various Countries

2.1.Introduction

In recent years, the problem of ecological damage has worsened. The exhaustion of resources and the environmental problems of energy exhaustion have become increasingly worrying. Building energy consumption in the construction, use, operation and maintenance of the building accounts for about 40% of the society's total energy consumption, and greenhouse gas emissions account for 30% of the total [1][2]. Traditional construction methods have always used extensive manual wet operation mode. There are product quality problems such as substandard performance, a large number of houses cracking, water seepage and leakage. The unreasonable development and use of resources and energy have caused many ecological and environmental problems such as soil erosion, soil desertification, and increased carbon emissions. Dust, noise, industrial waste, and construction waste generated during construction will exert unprecedented tremendous pressure on the ecosystem's own circulation. Therefore, the transformation of traditional extensive construction methods and the exploration of industrialized building design methods have become an effective way for people to solve the problem of contradiction between residential construction and ecological environment. The industrialized construction method combines advanced science and technology and construction theory. The product design quality is good, and the component production efficiency is high, so that the performance of the residential building has been greatly improved. At the same time, based on the concept of sustainable development, the industrial construction of the building has greatly reduced the consumption of resources and energy and the discharge of waste and garbage during the production construction. It is the development direction of the construction industry.

Prefabricated construction refers to the practice of manufacturing to build components in a factory, and then assemble them at the construction site [3]. It can bring many benefits, such as lower construction costs, higher construction speed, less construction waste, improve quality, reduce material consumption [4]. Prefabricated parts are also considered to be an effective way to achieve lean construction [5]. These advantages have promoted worldwide development. Prefabricated buildings have been used since 40 years ago [6], and it is reported that construction in the global prefabricated parts market will continue to grow at an annual rate of about 7% before 2020 [7]. In China, as a special manufacturing process, prefabricated construction ushered in new development opportunities and policy support as well as "Made in China 2025" [8].

In this chapter, the concept of prefabricated buildings is introduced. It analyzes the history of housing industrialization in various countries and regions and summarizes its development experience. This chapter also studies their advanced academic theories and summarizes the development laws of residential industrialization. In addition, combined with actual prefabricated construction engineering cases, the characteristics and applications of prefabricated construction development in various countries and regions are introduced.

2.2. Definition of prefabricated buildings

Prefabricated architecture refers to architecture created by applying a method called "prefabrication" to more parts than conventional construction methods. In other words, it refers to architecture in which parts are produced and processed in the factory in advance and assembled without being processed on the construction site and can be broadly classified into the following three types. First one is prefabricated house, detached/rental housing built for housing. Second one is PC (precast concrete) architecture, it is a high-rise building with concrete as the main structure. Last one is standard architecture, mainly refers to buildings for leasing or temporary business, which mainly consist of lightweight steel frames [9]. In this paper, prefabricated buildings refer to components and units(including the main structure, walls and stairs) manufactured by off-site factories, which are transported and assembled on site to form the entire building.

The construction method of industrialization was originally proposed and developed by developed countries such as Europe and the United States. The industrial revolution brought about a rapid increase in the urban population. Social problems such as housing shortages and deteriorating living conditions have followed. In order to protect the social housing problems of urban residents, countries put forward reasonable and targeted public housing construction strategies in light of their national conditions. After nearly a hundred years of practice, it is now relatively mature. Construction industrialization refers to the process of transforming the construction industry according to the industrial production mode, gradually shifting it from handicraft production to large-scale social production. Its basic approach is building standardization, factory production of structural parts, construction mechanization, and scientific organization and management. And gradually adopt the new achievements of modern science and technology in order to improve labor productivity, speed up the construction speed, reduce project costs, and improve project quality. Construction industrialization replaces the scattered and backward handicraft production methods of the past with centralized, advanced and large-scale industrial production methods. It achieves the goals of reducing labor use, improving residential quality, and shortening construction cycles. It includes the standardization of building parts and components; the integration of all stages of the building production process; the mechanization of parts production and construction processes; the scale of building parts and components production; and the high degree of organization and continuity of construction[10].

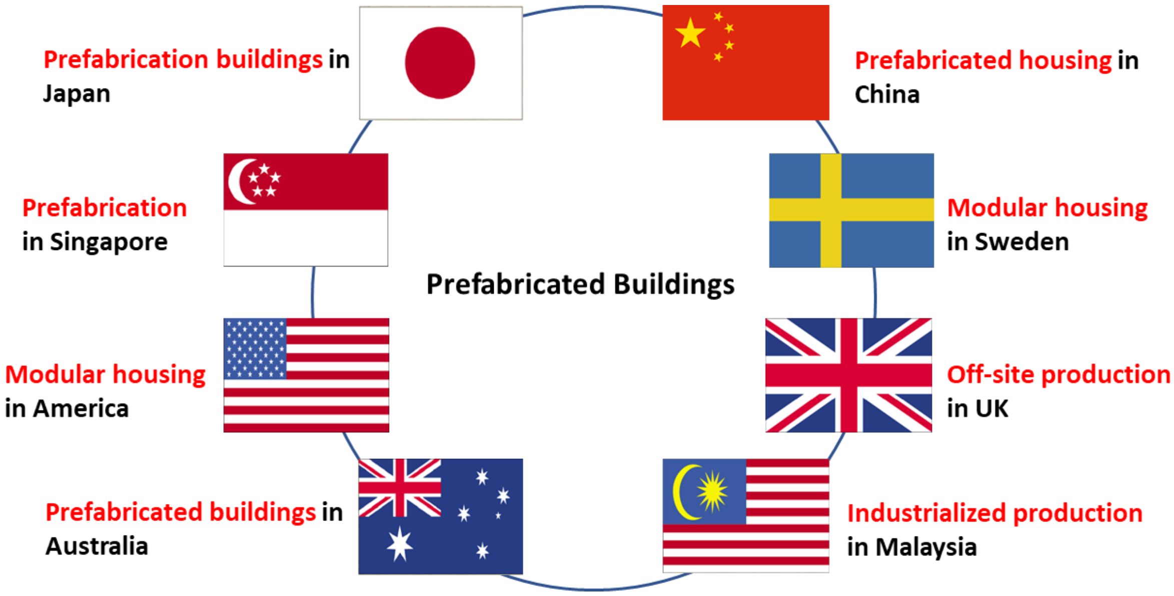


Figure 2.1. The term used to describe "prefabricated buildings" in various countries and regions

Prefabricated buildings have been developed rapidly since world war II and are widely used all over the world [6]. The term used to describe "prefabricated buildings" is slightly different in various countries and regions, for example in Figure 2.1, "prefabrication", "pre-assembly", "modularization", and "off-site manufacturing". Since 1955 (1955), the term "prefab" has been vaguely used in Japan as a general term for low-rise prefabricated houses, temporary school buildings / offices, precast concrete mid-rise apartments, etc. [11]. The Japan Prefabricated Construction Suppliers and Manufacturers Association (JPCSMA) was established in January 1963. It is an association consisting of a housing group (low-rise housing), high-rise buildings (medium-high-rise concrete apartments) and standard building groups (temporary housing, temporary teaching buildings, etc.). The establishment of the association promoted the application of the word "prefab". However, the term "prefab building" is just a common name, and it is called "manufacturing building" or "non-combustible prefabricated house" by the public under the loan category of housing finance companies [12]. In 1973, the preformed building performance certification system implemented by the Building Center of Japan used the name "Industrial Building Performance Certification System". This requires that the building not only has the characteristics of a shelter, but also requires the use of advanced manufacturing technology and industrial technology to improve indoor comfort. Since then, "industrial building" has become very popular in the architectural society and the housing industry. However, the JPCSMA continues to use conventional names, so the common name "prefab building" is also widely used in society. Therefore, the two names "prefab building" and "industrial building" are in use. When referring to performance, the main term is used "industrial building" [13]. The term used to describe "prefabricated buildings" is slightly different in various countries and regions, for example, "prefabrication", "pre-assembly", “modularization”, and “off-site manufacturing” [14]. “Modular housing” is used in America [15], “prefabricated housing” in mainland China [16,17], “prefabricated buildings” in Australia [8]; “prefabrication” in Hong Kong and Singapore [13,18], and “off-site production” in European countries [19], which refers not only to prefabs but also to elements like reinforcement structures (e.g., cages for columns) that are manufactured offside and mounted on site.

Tatum et al. [20] define prefabrication as a manufacturing process usually performed in specialized facilities, where various materials are combined to form an integral part of the final device. Gibb [21] regards off-site manufacturing as a process that combines prefabrication and preassembly. This process involves the design and manufacture of units or modules, usually away from the construction site. It also includes subsequent transportation and installation to form a permanent structure on the construction site. Although there is no single, widely accepted pre-defined definition so far, many common clues have been found from the definitions in the previous literature. These threads represent the manufacturing process during the construction phase and are characterized by: (1) off-site construction; (2) activities carried out in the factory environment; (3) prefabricated components built in the form of parts, units or modules in the factory (eg. floor slabs, facades, stairs, beams, bathrooms, kitchens, etc.); (4) transport prefabricated components to the project site, and (5) assemble and install them to form the entire building. Prefabricated buildings are products manufactured by the above method. The term "prefabricated" in the current study is marked as having the above characteristics. Commonly used building frame structural systems in prefabrication are light-pressed steel frames, precast concrete frames and wooden frames [21,22]. Prefabricated construction methods can be divided into three types, namely semi-prefabricated, comprehensive prefabricated and volumetric modular building [5]. Semi-prefabrication is a construction method in which certain elements of a building are cast on site, while the rest are made of factory-made components or units. In a comprehensive prefabrication, all building components are manufactured independently in the factory and then fixed together on site. Volume modular building refers to the entire building produced by the factory.

2.3. The development process and characteristics of prefabricated buildings in Europe and America

The concept of industrialized architecture originated in Europe in the 19th century. The rapid development of the Industrial Revolution has brought about innovations in construction methods and provided soil for the germination of industrialized buildings. At that time, the design practice was mainly concentrated in hall-type buildings such as exhibition halls and railway stations, or multi-storey factory buildings. The representative building assembled through standardized prefabrication is the London "Crystal Palace" built at the 1851 World's Fair (Figure 2.2). The Crystal Palace is not only an innovation of the construction method in structural engineering technology, but also a practical application of this construction concept in all aspects of design, production, transportation, construction and even demolition. This is also considered as the prototype of the construction process based on the concept of full life cycle. The Second World War caused massive destruction of the city, coupled with the "baby boom" and the demobilization of sergeants that followed the war, each country needed a lot of housing to rebuild. Research on houses (prefabricated houses) produced by factories in mass production has become active. This led to the second upsurge of prefabricated assembly in the construction industry, namely the development of construction industrialization. In the 1970s and 1980s, with the post-war economic recovery and technological development, the quality of construction products received widespread attention, ushering in another development period of industrialized construction.

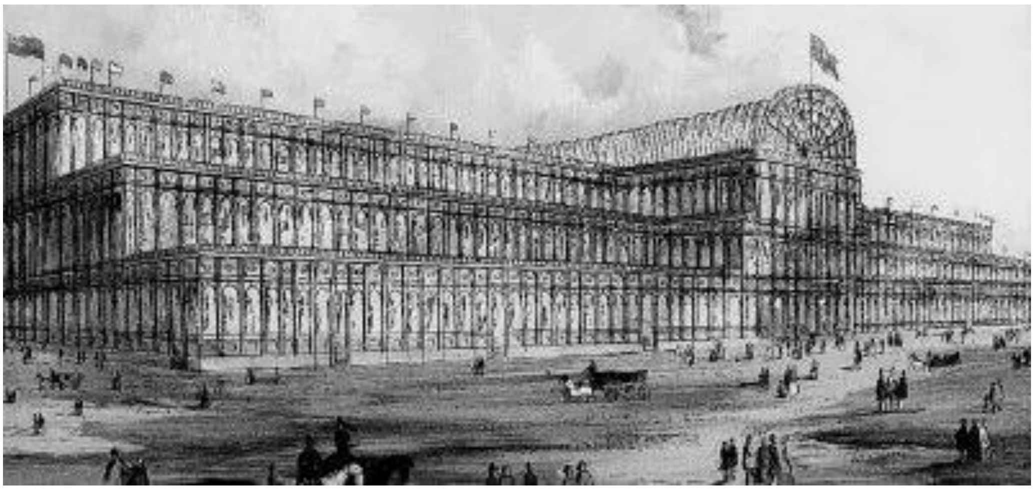


Figure 2.2. Crystal Palace [23]

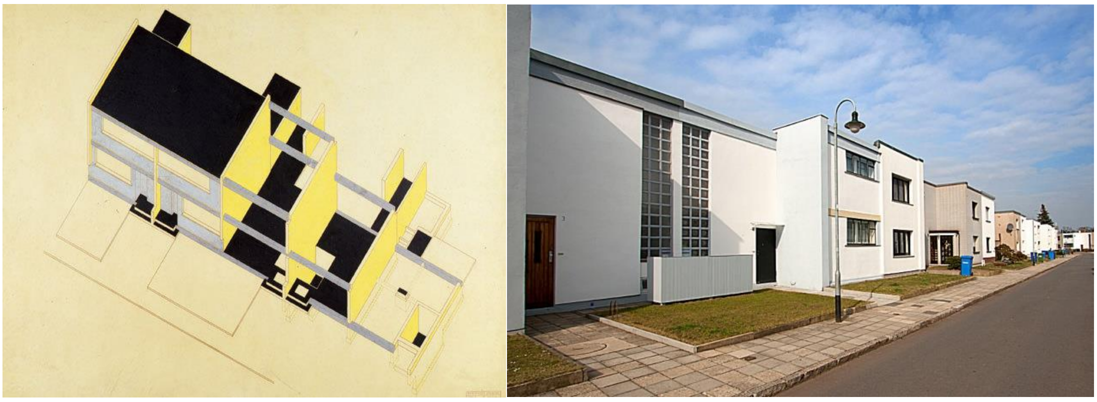
2.3.1. Late 19th Century-Before World War II: Early Development

At the end of the 19th century and the beginning of the 20th century, a large-scale urban population expansion occurred throughout Europe. After the First World War, the new population policy led to a rapid increase in the urban population and a sharp increase in the demand for urban housing. The traditional construction method is difficult to solve the problems faced at that time. There must be a new way of construction to change the status of social architecture. The industrial revolution and the application and popularization of reinforced concrete have brought more possibilities for the production design of the construction industry. The pioneer architect of modernism is relying on the emergence of new technologies and new materials to study low-cost construction. From the perspectives of production and construction, a new concept of constructing urban buildings by industrial means is proposed. Van Der Waerden proposed in 1918 to combine a limited number of standard units into more possible flat forms, and in this way concentrate the distribution of building materials and labor [23]. His idea became the prototype of the concept of industrialized production of construction: standardized prefabricated production, transportation and assembly, and organized these in an orderly manner [24]. What embodies this idea is Gropius' "Industrial Housing Principle" and Corbusier's domino housing system.

The industrial revolution in the early 20th century provided a tremendous driving force for social change. At that time, the contradiction of social housing became more and more serious. Under the social background at that time, the traditional construction method was obviously unable to meet the massive construction needs of the residence. Only the development of industrial construction can solve the contradiction between supply and demand of social housing. Gropius realized that the influence of the Industrial Revolution should also appear in the field of residential architecture. He tried to establish an industrial assembly system of "universal flat panel assembly system", hoping to solve the society's large number of residential needs through "limited standardized components to assemble unlimited possibilities" [25].

In 1913, Gropius published an article about "the development of industrial architecture". It includes about 12 photos of North American factories and grain elevators. This article had a profound influence on other European modernists, including Le Corbusier and Erich Mendelsohn. Both of them reprinted Gropius's grain elevator photos between 1920 and 1930 [26]. Gropius, together with many colleagues, tested different methods of industrial production logic that can be broadly classified into two different categories: flexible construction kits; factory mass production. Both methods aim to rationalize the design and construction process so that the house becomes a product in the sense of industrial manufacturing modern machine architecture.

In 1928, Gropius launched the "Toto Residential District" project that had a far-reaching impact on the subsequent industrial construction (Figure 2.3 and Figure 2.4). This is the first application of its industrial housing construction concept. It is also a landmark practice in the history of industrialized housing development. A terrace house with a kitchen garden and an area of 350 to 400 square meters was designed. According to the type of house, 314 townhouses were built during the three stages of construction. The construction area is between 57 and 75 square meters. These cubes are placed back to back to form a semi-detached house. They are combined in a combination of 4 to 12 units. The facade is divided by vertical and horizontal rows of windows. The interior decoration uses light tones [27]. The Reich Research Society for Economic Efficiency in Construction and Housing conducted extensive experiments in 1927. Various types of houses have been built to provide information about the rational manufacture of residential houses, as well as the suitability of new construction materials and industrial products. Each residential unit adopts a masonry structure, which is supported by a horizontal wall, and the longitudinal beams are connected in series by a reinforced concrete structure. On-site prefabricated structural components are transported by small railway trucks and moved by cranes. The cranes run parallel to the layout of the house to transport various prefabricated components built through standardized design and production. The construction efficiency of the project is very high. The duration of the entire project took only two months. Based on these projects, Gropius developed the concept of a flexible industrial production building kit. He described this in the article "Wohnhaus-Industrie". He advocated the transformation of the entire construction industry into industrial direction. The goal is to assemble houses as industrially produced products with highly flexible construction kit elements. Gropius suggested that building components should avoid pouring at the construction site and be produced in specialized prefabricated factories. The building components are produced in a factory-made way. Through dry construction methods, that is, by converting traditional cast-in-place buildings to industrial production, the shortcomings and deficiencies of traditional handicraft-like buildings will be avoided, such as defects in materials or structures, dimensional tolerances or the effects of seasonal weather. Gropius believes that in this way, construction can achieve the advantages and quality of industrial production. The price of the machined components is fixed, and the construction process is short and reliable. At the same time, he also noticed the deficiencies caused by industrial production [28]. He emphasized that industrialization is only a means of construction. The materials and technologies of mass-produced staircases, doors, windows and other building components should be designed and produced in order to provide multiple possibilities for combination and matching, and to achieve a perfect combination of art and technology. However, the backward industrial production capacity at that time did not meet Gropius' requirements for the diversity of industrialized buildings. This also led to the shortcomings of the single shape and function of the building during this period.



a. 3D model of Toto Residential Building b. Image of Toto Residential District

Figure 2.3. Toto Residential District [27]

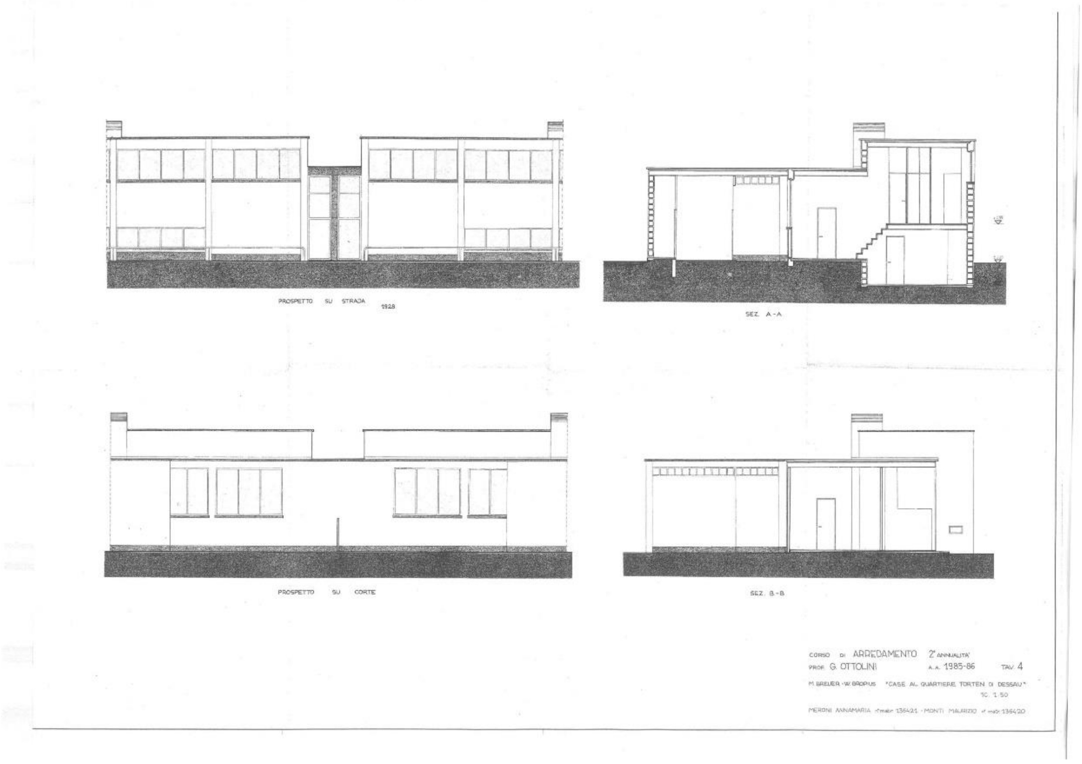


Figure 2.4.Elevation and section views [27]

Between 1914 and 1915, Le Corbusier, with the encouragement of his friend Max du Bois, envisioned a standardized building system using reinforced concrete, proposing "The house is an machine "for living in", which laid the foundation for the most cutting-edge architectural theories such as industrialized houses and residential machines [29]. This is a conceptual design for the design and construction of industrialized buildings. In the next ten years, this design became the basis of most of his buildings. These were once Dom-Ino prefabricated houses with independent skeletons. The Dom-Ino Houses (Figure 2.5) proposed by Corbusier, which combines the allegory of Domus (house in Latin) and various parts of the domino game. Because the floor plan is similar to a game, and the units can be arranged in a series like dominoes to group different modes of building. This model presents an open floor plan. The core of the building is the frame combination of independent columns and cast-in-place floor slabs. Supported by a minimum number of thin reinforced concrete columns around the edges of the concrete slabs, the stairwell provides access to each level of the floor plan. This structure makes the plan design very flexible. The simple and clear "open" method eliminates the beams of the load-bearing wall and ceiling, so that the internal configuration can be freely designed. The façade is allowed to be independent, and the windows are allowed to easily turn corners. These houses will be composed of standardized elements and connected to each other in a variety of combinations, creating the possibility for the continuous collective residential form they propose. This is not only a technologically innovative design method, but also a brand-new construction method. This industrialized construction method can provide a large number of low-cost and high-quality construction products better than traditional technology, while also making full use of labor and raw materials [30]. Corbusier ’s Marseille apartment is a masterpiece of Corbusier ’s industrialization thought. There are also Fermi Nivi and Haute apartments, Nantes apartments, Berlin apartments in Germany, and the Brazilian student apartments in the university city of Paris, all of which are the construction practices of Corbusier's industrialized housing. At this time, the industrialized building structure system showed a diversified exploration trend. However, due to the limitations of technology and market, they have not been promoted in practice, and are mostly experimental buildings.

Figure 2.5.Dom-Ino Houses [30]

The development of construction industrialization during this period was mainly the formation of the theory of industrialized design, production and construction. Through the discussion of the design of "minimum standard" residential units, the development of standardized design and industrialized production ideas is the sprouting of the industrialization development concept of the residential industry. The main features of this period are:

1) Large-scale "minimum standard" residential construction, with low construction cost and single housing design and functional design;
2) The idea of "dwelling is a machine for living" has a wide range of influences. The residential area lacks humanized design and ignores the possibility of neighbor’s communication；
3) A variety of structural systems have emerged, such as the mixed structure of brick walls and reinforced concrete, the mixed structure of steel and reinforced concrete, etc.

2.3.2. After World War II ~ 1970s: Batch Construction

The Second World War until the 1960s was the initial stage of the formation of the concept of industrial development of construction. During this period, a large number of industrial construction projects were developed. Countries have also established relatively complete industrial production systems in practice. The destruction of urban architecture by large-scale world wars has not only created the possibility for a large number of architectural constructions during this period, but also put forward a new and severe test for the urban construction methods of this period. In Germany, although the development of industrialization of construction in wartime was basically stagnant, the pioneer architects of modern architecture did not stop the research on the concept of industrial construction. In 1957, the West German government passed the Second Housing Construction Law (II.WoBauG), which will be built in a short period of time to meet the needs of most social class residents as first priority, including houses with appropriate area, facilities, and affordable rent, as residential construction. Le Corbusier built the Marseille apartment from 1947 to 1952. He likened the structural system to a reinforced concrete bottle rack built on site. The prefabricated apartment is inserted into the shelf like a wine bottle. Apart from the connection of pipes, the apartment should be fully assembled when it is inserted. It can be ensured to be installed directly on the site. Its design concept of industrialized construction methods and residential units has a positive impact on the promotion of residential industrialization. The first attempt of the precast concrete slab construction technology was carried out in Johannisthal in Berlin in 1953 in East Germany. In 1957, the construction of Hoyerswerda (Hoyerswerda) was the first large-scale construction of precast concrete components. Since then, East Germany has used precast concrete slab technology to build a large number of residential areas. The architectural style of the prefabricated concrete slab house is deeply influenced by the Bauhaus theory [31]. In 1961, Professor John Habraken, a Dutch architectural theory research scholar, published "Resident or user participation", which proposed a new concept of residential construction. Habraken studied architecture at Delft Technical University in Delft, the Netherlands, from 1948 to 1955. From 1965 to 1975, he served as Director of the Netherlands SAR (Foundation for Architects Research), researching and developing adaptive housing design and construction methods [32]. In 1960, Denmark's residential construction management agency proposed the "Residential Industrialization Plan." It also started Mass Housing construction activities starting from the 7,500-unit housing construction project that began in March of the same year. Sweden, like other countries, was facing housing shortages. This prompted the Swedish government to implement the "Million Housing" plan, which was the initial stage of the formation of industrialization of construction. It maintained a large-scale construction status in the 1950s and 1960s, and the number of newly built houses reached 62,225 in 1958 [33]. In order to solve the housing shortage problem, the French government began to use industrialization to build a large number of residential areas with relatively simple functions on the outskirts of the city.

After the 1950s, the population of the United States increased significantly after the war. The demobilization of soldiers, the influx of immigrants, and the military and construction teams also urgently need simple houses. There is a serious housing shortage. In this case, many owners started to buy travel trailers for residential use. So, the government relaxed the policy to allow the use of car houses (Figure 2.6) [34]. At the same time, inspired by it, some residential manufacturers have begun to produce industrial houses that look more like traditional residences, but can be pulled to large places and directly installed in various places. It can be said that automobile housing is a prototype of American industrialized housing. The industrialized houses in the United States are developed from RVs, so the style has not been very good. Most of its feelings in American hearts are low-grade, dilapidated houses. Due to social prejudice (for low-income families, etc.), most local governments in the United States restrict the distribution of this type of housing complex by a variety of policies and implementation methods related to the development of American prefabricated buildings. When choosing land, it is difficult for industrialized residences to enter the “mainstream society” land use area (a better location in the city or suburbs). This further strengthens people's psychological positioning of this product. It is difficult for its residents to enjoy the same rights as others.

Figure 2.6.Car Houses in the United States [34]

During this period, large-scale slab construction has become the main implementation technology for large-scale residential construction in Denmark, such as Larsen & Nielsen Industrialization Construction (Figure 2.7), etc. [31]. This construction technique includes large panels prefabricated by the factory (panel, stairs and walls). In this type of structural system, each large slab is supported by a load-bearing wall directly below it. Gravity load transfer only occurs through these load-bearing walls. This wall and floor system are installed in the slot. These joints are then bolted together and filled with dry powder mortar to secure the connection. During this period, developed countries such as the United Kingdom and France carried out research and application of assembled large-slab structural systems, and began to establish industrialized special design and production systems for residential wall panels, beams and columns. It effectively solved the massive demand for housing in postwar countries. At this stage, the owner entrusts the architect to design the building, and the construction enterprise and design unit jointly develop the "structure-construction" system. The components are processed and produced by the component factory according to the drawings. The design of the template is not standardized, and the production of components is more flexible. Although there are many practical projects that this system can follow, there is no unified design standard. At this stage, the demand is relatively large. Although its components are flexibly designed according to the requirements, each set still has a large enough production scale to ensure the reasonableness of the cost. The annual continuous contract was signed through the recognized industrial construction, which led to the large-scale plate construction represented by Camus Construction (Figure 2.8) and Coignet Construction being actively adopted. It is precisely because of these reasons that this stage has a "system, no standard" situation. At the same time, the former Soviet Union also focused on the development of heavy concrete slab systems in major cities such as Moscow and Leningrad. The large slab structural system adopts structural forms such as horizontal and vertical wall bearing, external wall bearing internal frame, large-span horizontal wall bearing The main structural components such as exterior walls, beams and columns are prefabricated in the factory, which greatly accelerates the construction efficiency and shortens the construction period. However, due to the limited level of component prefabrication technology, the component product types are simple, so that the produced residential buildings have the disadvantages of monotonous rigid appearance, single form of residential area, and lack of vitality. Although it solves the huge demand for the number of houses in the society, it also causes the problem of uniformity and lack of personality in urban houses. At the 1957 Berlin International Housing Exhibition in Germany, Gropius, Le Corbusier and many other modern architectural masters exhibited residential works that showed the feasibility of industrial construction of residential buildings. Take industrialized production and standardized design as a means and way to solve the problem of housing construction [28]. This exhibition also made a successful publicity and promotion for the concept of residential industrialization.

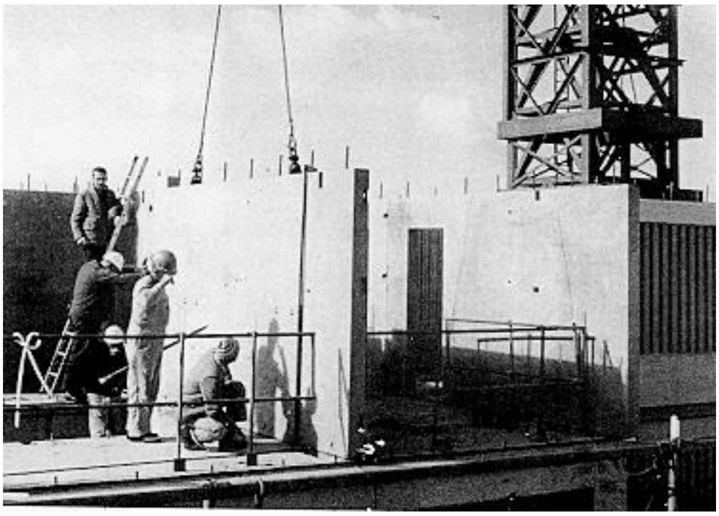


Figure 2.7. Larsen & Nielsen Industrialization Construction in Denmark [31]

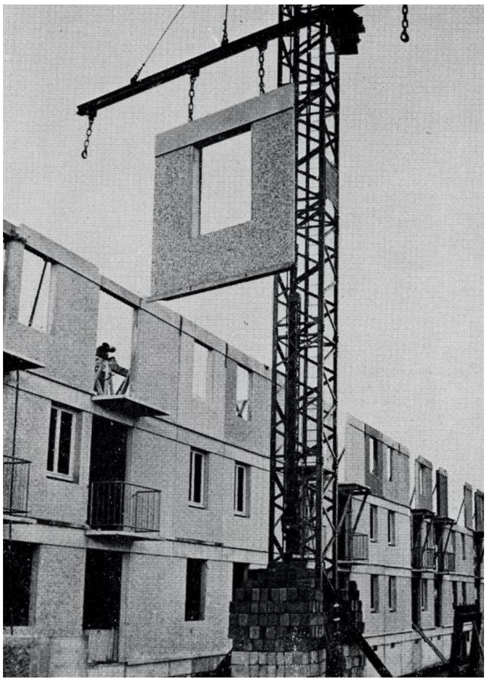


Figure 2.8. Camus Construction in France [31]

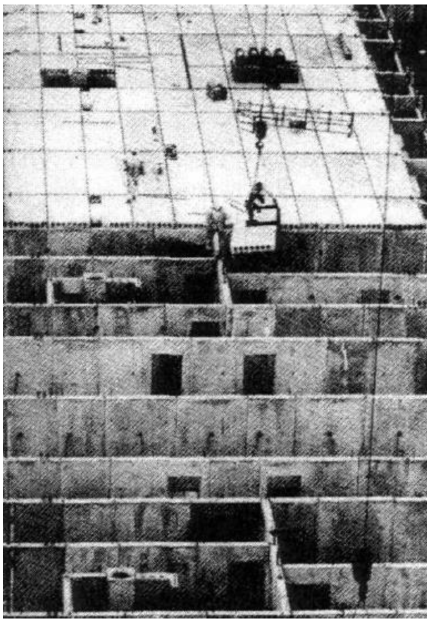


Figure 2.9. Prefabricated building in Sweden [35]

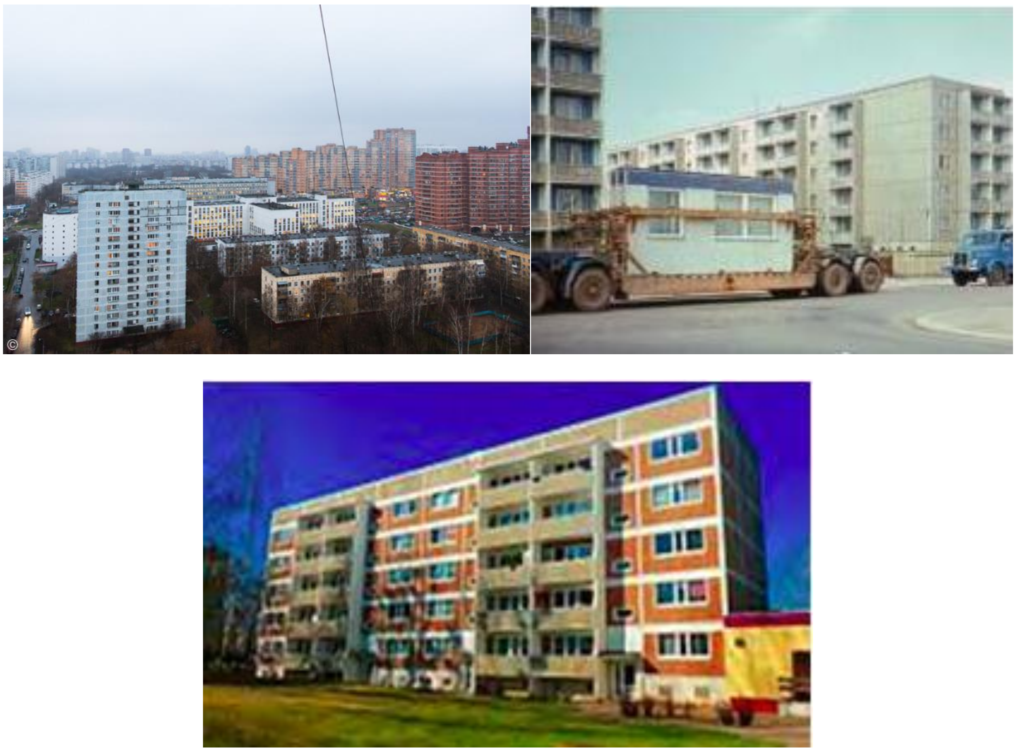


Figure 2.10. Prefabricated building in Germany [28]

In the early stage of the development of residential industrialization, in the face of the social problems at the time of a sharp housing shortage, solving the problems of housing construction quantity and standard industrial production design methods and other issues became the main goal of this period. The low-cost, efficient construction of industrialized residences has created the possibility of large-scale residential construction. However, the problems of monotonous layout, lack of humanistic care and personalized design were also exposed. Industrialized housing must develop in the direction of diversification in shape and layout. The main features of this period are:

1) The standardized design of residences resulted in simple forms and lack of personality. The layout of the settlement was in the form of barracks;
2) Various countries carried out the work of establishing a special system for industrialized design and production, and used prefabricated components for large-scale residential project construction;
3) The diverse expressions of building materials are beginning to be noticed. The design of residences has evolved from simplification to diversification. Neighborhood relations in residential quarters and people-oriented architectural design are valued.

2.3.3. The 1970s and 1980s: Quality Improvement

The 1970s and 1980s were a period of great development in industrialized housing construction. The quality of residential products has received widespread attention. Housing construction is no longer simply pursuing quantity growth. The functional transformation of the completed houses was carried out to meet the high standards and requirements of the society for the quality of living space. This period is also known as "the second generation of construction industrialization era."

The Swedish government has always attached great importance to the standardization of residential industrialization. As early as the 1940s, the Institute of Building Standards was commissioned to study the coordination of modules in residential design. The Building Standards Association (BSI) conducts research on building standardization [35]. In the 1960s, the standardization of building components was gradually incorporated into the Swedish Industrial Standard (SIS). The design and production of parts and components follow the standard specifications, providing material possibilities for the circulation and interchange of parts and components between residential products. At the same time, the Swedish government enacted the Residential Standards Act in 1967, which stipulates that as long as construction materials and components manufactured in accordance with the building standards of the Swedish National Standards Association are used to build a house, the construction of the house can obtain government loans [35]. At the same time, guidance from the policy level has promoted the development of a general system for industrialized housing.

In 1977, France established the Component Architectural Association (ACC) to develop structural parts and housing parts to achieve modular coordination, thereby establishing a universal structural system. In 1978, ACC established modular coordination rules. In the same year, a "construction system" began to form as a means of excessive open industrialization. It is a main structural system, which is composed of a series of mutually replaceable stereotyped components, thus forming a general catalog of components [36]. Architects and design members can choose components to form diverse buildings like building blocks. Architects must choose the components of the catalog, and they must follow certain design rules in the architectural art or be subject to certain restrictions. The French government does not advocate a nationwide construction system. Instead, it advocates a batch, but not too much, so as not to affect the scale of use of a single structural system and affect economic efficiency. By 1985, France had formed 25 residential industrial building systems, most of which were precast concrete structural systems [36].

Since the 1990s, there had been basically no new projects constructed with precast concrete slab technology. Instead, it pursued personalized design and applied modern, environmentally friendly, beautiful, practical, and durable comprehensive technical solutions to meet the needs of users. Through refined and modular design, many construction parts could be processed in the factory. And the technical system was constantly optimized, such as recyclable formwork technology, stacking and floor slab (free formwork) technology, prefabricated stairs, and a variety of composite prefabricated external wall panels. Adapted to local conditions and do not pursue high assembly rates. The Tour Total building with precast concrete facades was completed in Berlin in 2012, which represented a development direction for precast concrete prefabricated buildings in Germany.

In 1976, the US Congress passed the National Manufactured Housing Construction and Safety Act (HUD). In the same year, HUD was responsible for promulgating a series of strict industry standards and standards that have been used to this day. In addition to emphasizing quality, industrialized houses nowadays pay more attention to improving aesthetics, comfort, and personalization to avoid monotonous facade shapes caused by mass construction. While ensuring quality, designers and enterprises also pay attention to the shaping of beautiful and personalized facade shapes. The appearance of many industrialized residences was like that of non-industrial residences. New technologies were constantly being introduced, and energy conservation was also a new focus. This shows that the industrialized housing in the United States has undergone a phased transition from pursuing quantity to pursuing quality.

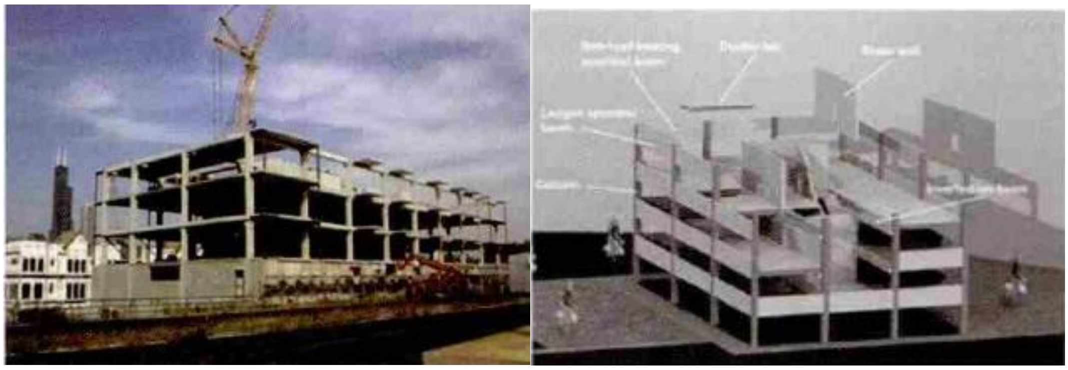


Figure 2.11. Prefabricated Building in America [34]

During this period, people have begun to pay attention to the design flaws left over from the previous development stage. The uniform appearance of residential areas brought about by standardized design and industrialized production was beginning to receive more and more criticism. The design of industrialized houses must be developed in the direction of personalized and diversified design. The residential industrialization construction in this period showed the following characteristics:

1) The housing problem has been basically solved through the large-scale construction of houses in the previous stage. The speed of industrialization slowed down, and gradually turned to the comfort and personalized design of industrialized houses. Residential design began to focus on the upgrading of living quality and the improvement of comfort satisfaction;
2) The emergence of new composite materials and the improvement of industrial technology have brought more possibilities for the diversified design of industrialized houses;

3) The industrialization of housing has been further developed. The design and construction of industrialized residences transitions from a dedicated system to a universal system. The diversification and personalized design of industrialized houses have received more attention.

2.3.4. From the end of the 20th century to the present: mature development

After the 1990s, global environmental problems have become increasingly serious. In 1989, at the 11th meeting of the International Construction Research and Documentation Committee (CIB), the development of construction industrialization was officially listed as one of the eight major development trends of construction technology in the world. Building construction began to develop in the direction of resource and energy recycling and green development and sustainability. The development of construction industrialization has also entered a mature stage. At this stage, based on optimizing building components and structural systems, a sustainable and industrialized development system combining functionality, durability, aesthetic characteristics and environmental protection was explored. In order to meet the needs of future transformation, modular design methods and parts system began to be developed.

The UK has always been committed to the development of Modern Methods of Construction (MMC). Construction products produced by the MMC construction method have long been evaluated by people as having only industrial machinery and icy appearance, lacking personalized expression, and even losing their modern beauty. After experiencing a large-scale residential construction period, the British construction industry gradually began to reflect on the affiliation between buildings and users. Design and use details were concerned. Combined with the local environment, they developed the advantages of industrial production construction, improved the quality of construction products, created a pleasant living environment, and provided a healthy and environmentally friendly lifestyle. In the process of scheme design, designers deliberated on the combination of materials and technology, grasped the connection between the whole and the part, and showed the mechanical beauty of industrial buildings.

With the development of science and technology, global relations are getting closer and closer, and the ecological environment shared by mankind is more and more valued by everyone. The pollution and destruction of the environment by traditional construction methods no longer conforms to the healthy development objective of the modern construction industry and will be replaced by new industrial construction methods. In the new development stage, the industrialization of construction also presents new characteristics:

1) Industrial construction methods have gone through the historical stage of mass construction and quality improvement. The development stage of the new generation requires more industrial design concepts to pursue urban texture and pay attention to issues such as energy use and

environmental pollution;

2) Due to global ecological and environmental problems, green design and green production should also be developed in the process of building construction, and the sustainable development possibilities of all aspects of construction should be considered within the full life cycle of the building.
3) The construction technology based on the Internet and artificial intelligence is applied to prefabricated buildings, making prefabricated buildings intelligent and automated.

2.4. The development process and practice of prefabricated buildings in Japan

After the Second World War, Japan faced a lot of reconstruction work, which promoted the research of prefabricated buildings. The development of prefabricated buildings in Japan is relatively complete and has been widely used. It has achieved success in management and formed a large enterprise group with prefabricated housing as the main body. The proportion of new prefabricated buildings in Japan each year is shown in Figure 2.12. The reason why this ratio is very small is that only buildings that meet the certification of factory buildings and are constructed using prefabricated construction methods can be defined as prefabricated buildings. Therefore, not all buildings that use prefabricated components can be called prefabricated buildings. This condition is very harsh. The main residential style of the Japanese is low-rise housing in the city, and the market enjoyed is not as scattered as in the United States but concentrated in relatively narrow areas. The Japanese industry and construction industry not only regard this method of construction as a method of mass production, but also promote it as a modern industrialized house that emphasizes performance and function. In addition, it has a major impact on the introduction of prefabrication methods and the integration of advanced components of traditional construction methods. It has made a tremendous contribution to the improvement of the quality of the entire Japanese housing industry.

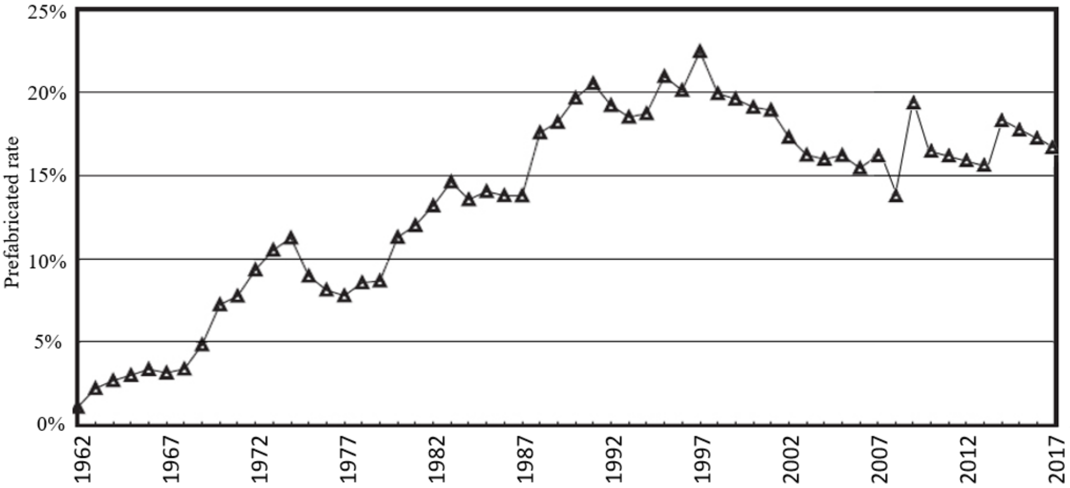


Figure 2.12. The proportion of new prefabricated buildings in Japan

2.4.1. The development trend of prefabricated houses in Japan before the war II

Before the Second World War, the Gropius effect and the influence of American industrialized buildings made Japan realize that modernization of building production should be strengthened. Ken Ichiura's "Rationalization of Construction Production" believes that in terms of the economic scale of residential buildings, rationalization and industrialization are very important, and architects should participate more[37]. Naoki Takagi's analysis of Trocken Montage Bau's relevant prefabricated building theory and published the details of research on dry technology [38]. In the same period, designers who focused on industrialized buildings also announced residential projects based on prefabricated construction methods [39]. At this stage, the construction company has developed a wooden "panel detached house" and is conducting experiments (Figure 2.13). Relevant design experience and engineering experience became the technical foundation of later wooden prefabricated houses in Japan [40]. In addition, there are related scholars focusing on the research of reinforced concrete prefabricated buildings. Compared with the characteristics of traditional Japanese buildings, reinforced concrete buildings have better fire resistance and durability, which is the future development direction of building structures. However, this new structure is different from traditional Japanese wooden buildings and has a higher cost. At that time, people's acceptance was low, and it was only used for the construction of some factories and public buildings. During the war, research on prefabricated buildings was forced to stop.

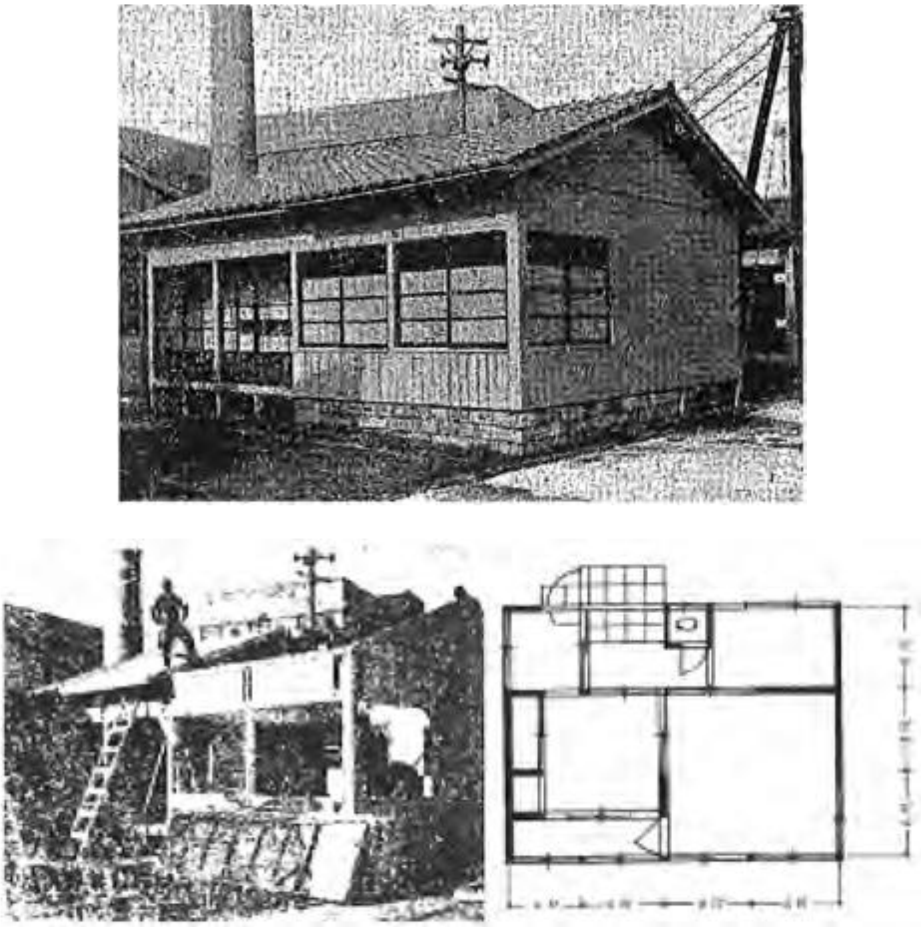


Figure 2.13.Panel Detached House in Japan [40]

2.4.2. Recovery period after World War II (1945-1960)

Japanese housing was severely damaged during the Second World War, especially in urban areas. The housing problem was exacerbated by the post-war demobilization and the baby boom of the 1945, the increase in population and the influx of people from rural to urban areas. In order to solve the housing problem and restore the post-war Japanese economy, the government promoted a construction plan centered on the reconstruction institute [41]. The country established a system and invested money, but it was not until the mid-1945s that the Japanese economy slowly began to recover. Due to lack of funds and construction materials, the reconstruction work is slow. As a result of the Korean War that broke out in 1950, Japanese industry finally recovered, and the supply of industrial products and building materials was gradually enough. Since then, Japan has begun to enter the post-war reconstruction stage. At this stage, based on the previous research, prefabricated low-rise residential and industrial plants were successively launched, as shown in Figure 2.14 and Figure 2.15.

Figure 2.14. Prefabricated Wooden House in front of Osaka Hankyu Umeda Station, 1950 [41]

Figure 2.15. Prefabricated Industrial Plants,1950 [42]

During the same period, some companies and research institutes are also conducting research on prefabricated concrete buildings. The more famous one is "Assembling Refractory Construction Co., Ltd.". However, due to technological limitations at the time, these studies encountered obstacles in application. Architect Kishida Shizuto (professor of the University of Tokyo and president of the Japanese Architectural Society) at that time made it clear that he wanted to develop prefabricated houses, but he would not place orders for the current prefabricated house [43], which also reflects the status of concrete buildings. However, relevant research institutions and enterprises have not stopped their research, which has laid the foundation for the future large-scale application of prefabricated concrete buildings in Japan.

Beginning in 1955, the Japanese economy finally began to grow, and housing demand began to rise. At this time, Japan announced a 10-year housing construction plan 14 (planned 250,000 units) low-rent housing project. The project funds come from housing construction financial institutions, which mainly provide multi-story low-rent houses made of reinforced concrete. With the recovery of heavy chemical industries such as cement and steel, construction materials have begun to stabilize. Considering the fire resistance requirements of buildings, precast concrete buildings began to be applied. Toyota Concrete Co., Ltd., a subsidiary of Toyota, was one of the first companies to develop low-rent government housing. The company's housing is mainly used for single-family houses or multi-story houses with thin ribbed concrete slabs (Figure 2.16). Precast concrete buildings based on this technology have not been widely popularized. But this technology laid the foundation for the subsequent precast concrete technology. In 1955, the house of Japan Yamato Housing Industry Co., Ltd. was born. It was the first prefabricated building in Japan that was completely built by the private sector and financially successful (Figure 2.17). This prefabricated building was released in 1959. Nobuo Ishibashi, the founder of Daiwa House Industry, decided to design a single-story building without construction approval documents. The price is less than 40,000 yen per square meter and can be assembled in 3 hours. It was widely accepted at the time because of its low cost and ease of mass production and proposed a new sales model-sold in department stores and other places.

Figure 2.16.Toyota A-type Precast Concrete Building [44]

a. Prefabricated Building Exterior b. Prefabricated components

Figure 2.17.Prefabricated Building in Japan [44]

2.4.3.The period of rapid economic growth ((1960 ~ 1973)

Compared with the previous period, the area of newly built buildings in this stage increased rapidly (Figure 2.18). In order to achieve the goal of new construction area, prefabricated buildings were widely promoted during this period. Various prefabricated construction companies have successively launched a variety of prefabricated construction products.

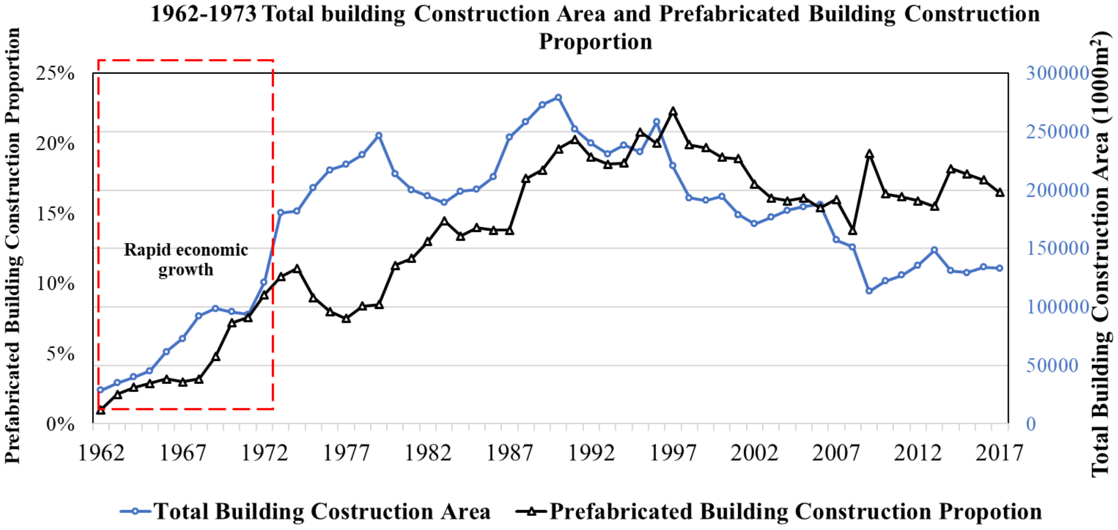


Figure 2.18.Total building Construction Area and Prefabricated Building Construction Proportion From 1962 to 1973

In 1960, the Building Materials Division of Sekisui Chemical Industry Co., Ltd. established the Housing Division. Began to develop a Sekisui House type A (Figure 2.19) using iron, aluminum and plastic as part of it [44]. In 1961, Panasonic developed its first lightweight steel structure, as shown in Figure 2.20. In the same period, the Yamato House and Sekisui House announced the Yamato House Type A (Figure 2.21) and the Sekisui House Type B (Figure 2.22) respectively. These two types of prefabricated houses are the prototypes of prefabricated houses.

Figure 2.19. Sekisui House type A [44]

Figure 2.20. Panasonic House Type One [44]

Figure 2.21. Yamato House Type A [44]

Figure 2.22. Sekisui House Type B [44]

Initially, this prefabricated building was the main type of single-storey building. In the later period, it gradually developed into a two-story building and added a garden design, which increased consumers' desire to purchase, as shown below (Figure 2.23 and Figure 2.24). Chiyoji Misawa, who developed the "board bonding method", built a prefabricated house at Misawa Lumber Co., Ltd. And in 1963 and 1967 announced a two-storey medium-sized wooden building. Since then, manufacturers of wooden prefabricated houses such as Yongda Sangyo have begun to pay attention.

Figure 2.23. Sekisui House Type 2B [44]

Figure 2.24. Yamato House Kasuga Type [44]

In 1961, under the guidance of the Ministry of Construction, a "prefabricated building round table" was established. In 1962, the "Construction Production Modernization Promotion Committee" was established. In January 1963, the two associations merged into the "Prefabricated Construction Association". Both the government and the private sector have high enthusiasm and expectations for the popularity of prefabricated buildings during this period. Scholars and the government pointed out the backwardness of Japan's housing production system and believed that it should be industrialized into a modern industry [45,46]. Previously, the main decision-makers and designers of prefabricated buildings have been construction engineers. In order to improve the development of prefabricated buildings, the chemical, electrical machinery, steel making, machinery, wood industry and major general contractors are included in the development system. This transformation has trained many prefabricated technical engineers. At the same time, other countries have high expectations for the industrialization of housing. In Europe, it is mainly apartments made of concrete. In the United States, low-rise detached houses and townhouses are booming. In 1969, the Housing Authority (HUD) held an ambitious proposal competition called Operation Breakthrough (Figure 2.25) [47]Inspired by this operational breakthrough in the United States, the Ministry of Construction of Japan held the “Pilot House Proposal Competition” in Japan in 1970. In 145 applications from 112 companies, 17 technical ideas (16 companies) were selected. Seven were selected in the field of independent. Since then, it has greatly stimulated the technological development of each company [48].

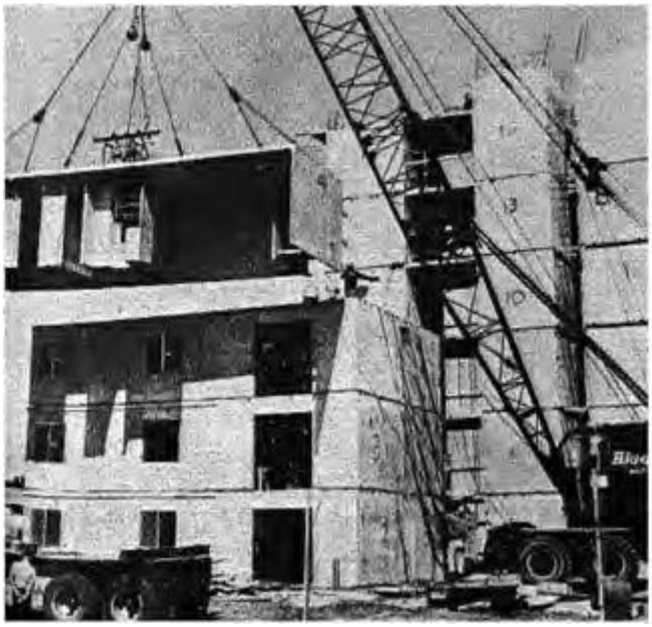


Figure 2.25. One Case of Operation Breakthrough

2.4.4.The period of stagnation caused by the oil crisis (1974 ~ 1985)

Due to the economic crisis triggered by the sudden oil shock in the fall of 1973, housing construction in Japan began to stagnate. As shown in Figure 2.26, by 1974 it had dropped sharply by more than 30%. Prefabricated construction companies have been hit hard by excessive capital investment and inefficient sales networks. Many companies that initially took the original business as a sideline started to quit. Although the construction market began to recover in 1975, it fell again due to the second oil crisis in 1978. Prefabricated construction companies in this era already have considerable capital investment and sales networks. How to formulate survival strategies has become a major issue. Some prefabricated construction companies will undergo qualitative changes.

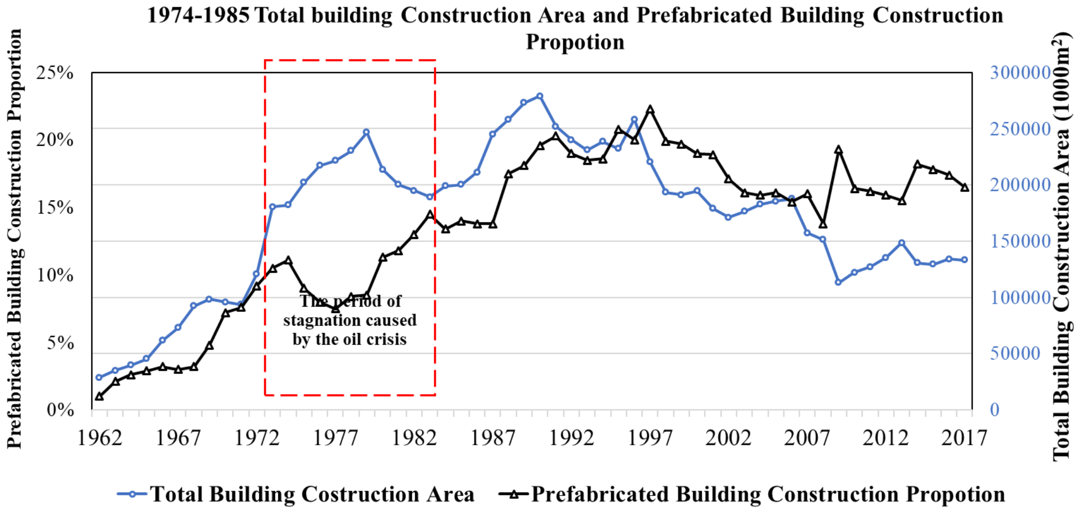


Figure 2.26. Total building Construction Area and Prefabricated Building Construction Proportion From 1974 to 1985

At this stage, the goal of prefabricated construction enterprises is to manufacture buildings similar to conventional ordinary houses. During this period, the construction level of the building has been greatly improved than before, which can meet the individual needs of different customers. However, due to cost issues, prefabricated construction companies do not yet have the technology for small batch production. Plan-proposed housing was developed under this background. Misawa Homes O type is an epoch-making type in the industry (Figure 2.27) [44]. In the past, the floor plan was partially common on the second floor, but the floor layout of this new prefabricated building can be changed.

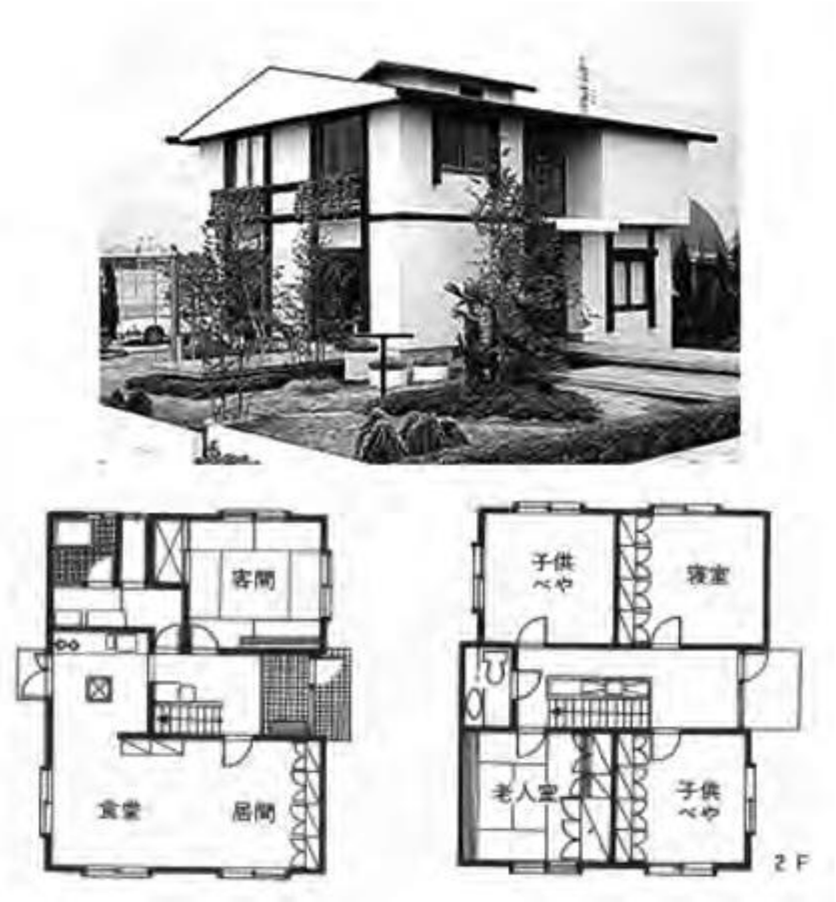


Figure 2.27.Misawa Homes O type [44]

During this period, the share of prefabricated houses (which used to be about 16% for a while) gradually weakened. One reason is the withdrawal of many prefabricated housing companies. But there is also a big reason for the factory production costs that cannot be reduced. In 1976, the Ministry of Construction and the Ministry of International Trade and Industry (METI) held a proposed competition "House 55 Plan" 21), with the aim of reducing costs through technological innovation and developing a 5-million-yen house. The construction industry has responded very well to the proposed competition. A total of 90 companies from 20 teams submitted applications. Among them, the TOPS group (Takeaka Works, Nippon Steel, Panasonic Electric Works), Misawa Housing Group, and Shimizu Construction Group selected three proposals. After that, through the research and development of each company, it was commercialized and implemented as "Misawa House 55"(Figure 2.28), "Kobori House 55" (Figure 2.29) and "National House 55" (Figure 2.30) [44]. According to the suggestion of Shimizu Construction Group, Kobori Sumiken has only conducted continuous research and commercialization of Kobori House 55 (which has not yet arrived and has continued technically until now).

Figure 2.28. Misawa House 55, 1980 [44]

Figure 2.29. Kobori House 55,1980 [44]

Figure 2.30. National House 55 [44]

2.4.5. Economic recovery and the real estate bubble period (1985-1991)

In the four years from 1987 to 1990, more than 1.5 million housing units were built every year. Even within a period of time after the bubble burst, the area of newly built residential buildings has maintained a certain increase, as shown in Figure 2.31. During this period, the proportion of prefabricated buildings in the total number of housing construction were also close to 20%. The goal of prefabricated construction companies was to provide high-end, high-quality houses, which have changed from pursuing the number of constructions to pursuing the quality of the houses.

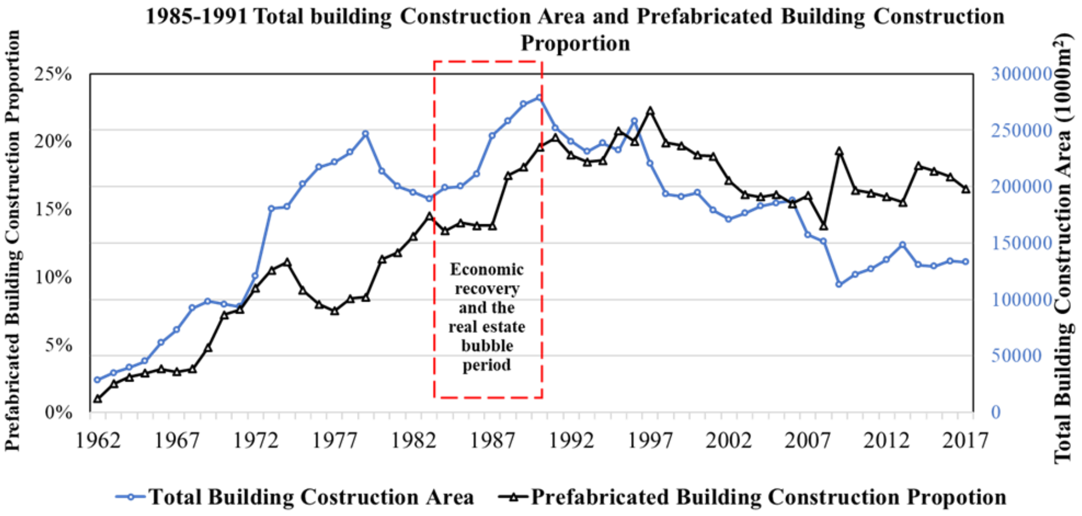


Figure 2.31. Total building Construction Area and Prefabricated Building Construction Proportion From 1985 to 1991

The following are some application examples of prefabricated buildings at this stage (Figure 2.32-Figure 2.36) [44]. At this stage, the government and relevant financial institutions were also inducing the prefabricated construction market in terms of policies and funds to promote the development of prefabricated construction towards high quality. In (1985), on the basis of the advisory opinions of the “High Standard Housing Round Table”, the goal was to form high-quality housing that will become the basis of life in the 21st century. It would improve living standards, respond to new needs and pay attention to regional characteristics, and launch a new "high standard housing premium loan system", which is applicable to all prefabricated buildings. At the same time, the Prefabricated Building Association had established high-standard standards on this basis and has also promoted improved residential comfort in order to strive for more markets. It also proposed a certification system for "excellent prefabricated buildings". The following considerations included: (1) welfare that focuses on the comfort of the house; (2) the composition of the family members of the residents; (4) the reasonable application of advanced equipment, (5) Response to future lifestyle changes.

Figure 2.32. Gournier EX (Sekisui House, 1985) [44]

Figure 2.33. Hefeng (Daiwa House Industry, 1987) [44]

Figure 2.34. Hebel House Cubic, 1986 [44]

Figure 2.35. Parfait (Sekisui House, 1987) [44]

Figure 2.36. Sunstate Sera（National House, 1987）[44]

2.4.6. Ten years of the collapse of the economic bubble (1991-2002)

The collapse of the bubble economy, especially the collapse of the real estate bubble price, led to asset deflation and caused severe social unrest. The economic recession that began in 1991 began with a sharp fall in land prices. Although the reconstruction of the Great Hanshin-Awaji Earthquake in 1995 and the consumption tax increase in April 1997 were relatively strong, the housing construction fell sharply from 1997, as shown in Figure 2.37. To deal with this crisis, the construction industry had put forward some suggestions, such as rationalizing the tax system and formulating regulations to promote housing construction in this era. The Hanshin Awaji Earthquake that occurred on January 17, 1995 caused a large number of casualties and property losses. 100,000 buildings were completely destroyed, and 150,000 buildings were partially or partially destroyed. In this earthquake, the damage of prefabricated buildings was very low, and no houses were collapsed or extensively damaged. This verifies the good seismic performance of prefabricated buildings, as shown in Figure 2.38.

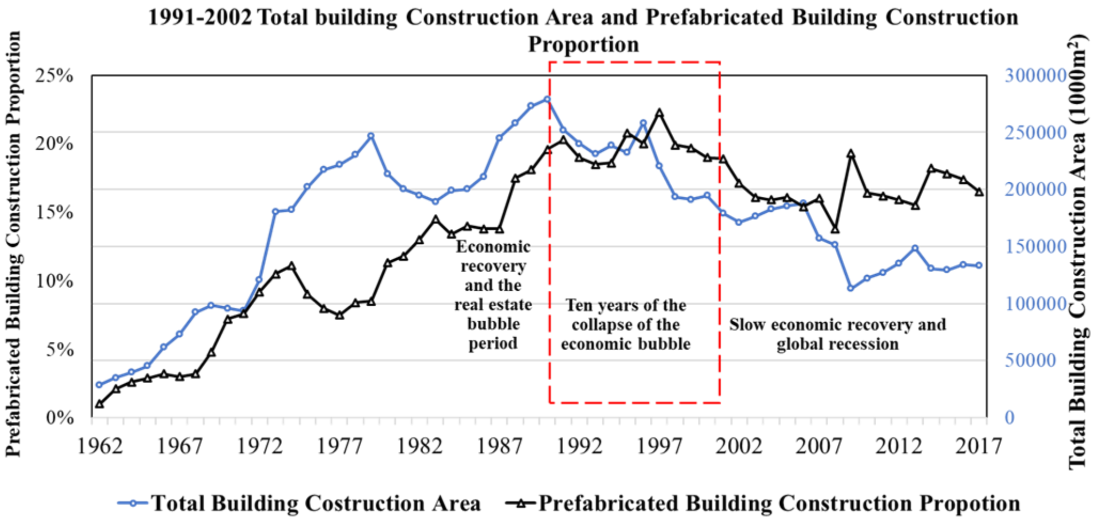


Figure 2.37. Total building Construction Area and Prefabricated Building Construction Proportion From 1991 to 2002

Figure 2.38. Prefabricated buildings after the earthquake

At this stage, the goal of prefabricated construction companies was to improve the safety of buildings. The "Industrial Housing Performance Certification System" was used to certify the performance and quality of assembled buildings. The regulation was promulgated in June 1999. Although not all houses are required to enforce this rule, consumers with this prefabricated construction could buy with confidence. The three main points of the regulation were: (1) "Housing Performance Rating System". This system could compare the performance of the prefabricated building you want to buy with other houses. Show the house standard through the "performance evaluation report" and give the house performance level. (2) "Dispute Resolution System". For houses that have been evaluated for building performance, once a dispute arises between the contractor and the owner, it would be handled by a third-party processing agency so that the dispute can be resolved fairly. (3) Mandatory housing "responsibility system for housing defects". This applied to all new houses built after the law comes into effect. Construction companies must repair these defects free of charge within 10 years after construction was completed and delivered. The content that should bear the responsibility of defect guarantee was divided into two parts. One part was the basic structural components such as building foundations, walls, columns and roofs. The other part was the roof and the opening of the outer wall to prevent the intrusion of rain. With the revision of the "Building Standards Law" in 2000, the certification of industrialized houses was changed to "type conformity certification system", and the relevant parts of Article 38 of the old law and the Ministry of Construction Circular No. 1790 of 1980 were deleted. The system included not only industrialized housing, but also construction equipment that is mass-produced with the same model, such as elevators, and the transition period from the old certification standards until May 2002.

2.4.7. Slow economic recovery and global recession (2002-present)

Due to the collapse of the bubble economy and ultra-low interest rate policies, a large amount of capital has entered the financial industry. Although Japan's continued economic downturn has increased slightly since 2003, the annual construction area was less than 2 million square meters (Figure 2.39). In the era of falling birth rate and aging population, and falling population, the shrinking construction industry has become a major problem facing the prefabricated construction industry. During this period, due to stagnation in demand, some prefabricated construction companies reorganized, and also expanded related businesses, such as the expansion and renovation of apartments and commercial facilities.

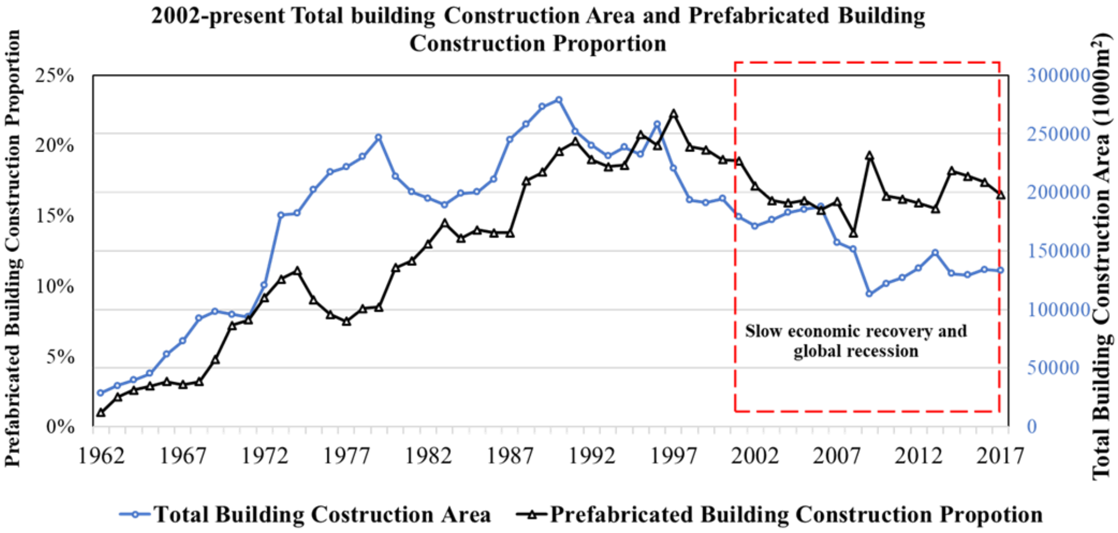


Figure 2.39.Total building Construction Area and Prefabricated Building Construction Proportion From 1991 to 2018

Sekisui Heim is the world's first company to construct houses using the Unit Construction Method. The company's production process has been and still is a continually evolving pursuit of quality and efficiency, and in its Kyushu factory, "robotic house construction" utilizing industrial robots is happening. Taking a closer look at the robotic automation process, shows that it can be divided into 4 parts as illustrated below (Figure 2.40). Kawasaki robots are used in processes 02–04. At present, the prefabricated building construction keep a stable proportion. To improve the energy efficiency and reduce environmental impact became more important. There were 49.99 million households in Japan, and the housing stock were 55.59 million. Through simple calculations, the vacancy rate reached 13.1% [49]. In terms of quantity, the existing housing stock meets housing needs, so it is necessary to study the treatment of vacant houses. In the United Kingdom, the average life expectancy of a residence was 75 years, Japan was 30 years old, and the United States was 44 years old. Therefore, it was considered necessary to formulate a basic housing policy to improve the Japanese building life cycle. The "Law on Promoting the Construction of Long-term Quality Housing" was promulgated in June 2006. The basis is (1) to provide high-quality housing, (2) to create a good living environment, (3) to protect and promote the profit of buyers, and (4) to ensure stable housing.

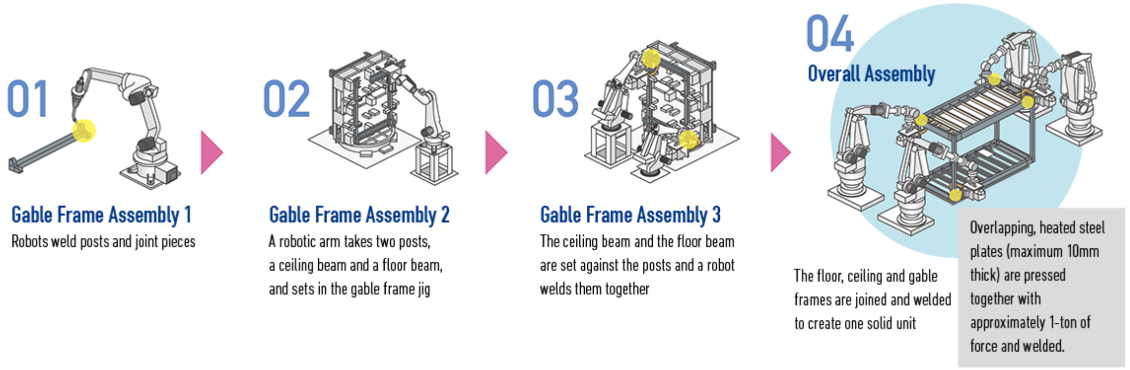


Figure 2.40.The robotic automation process in building production of Sekisui Heim

2.5. The development process and practice of prefabricated buildings in China

In the 1950s, China began the development path of industrialization of construction. Like many countries, construction industrialization has experienced a long and tortuous development process. This section combines the research of related literature, starting from the production mode and social background of China's construction industrialization, and divides the development process of China's construction industrialization into the following stages:

2.5.1. 1949 ~ 1975: the early stage of development

In the early days of the founding of New China, the country carried out large-scale housing construction. In the 1950s, it was proposed to learn from the Soviet Union the experience of industrialization construction and the principles of design standardization, industrialization, and modularization. There have been many discussions and practices on industrialization and standardization in the development of prefabricated components and prefabricated assemblies in the construction industry. Promoted the standard design of buildings and carried out the application and research on various building structure systems such as brick-concrete structures and reinforced concrete structures. At this stage, for the purpose of building many buildings, the establishment of construction industrialization industry institutions, to formulate industry design standards. In Beijing in 1957, China carried out the construction of the first prefabricated building, which adopted a vertical wall load-bearing scheme [50]. Floor slabs, blocks, light partition walls and roof tiles are factory prefabricated, and prefabricated components are assembled on site (Figure 2.41). Since then, China has embarked on the road of development of industrialized housing construction with "development design and production standardization, construction and assembly mechanization". In the 1960s and 1970s, the standardization method was further improved by drawing on foreign experience and combining national conditions. There have been certain improvements in construction technology and speed. In the 1980s, it was proposed: "standardization of design, production and industrialization of structural parts, mechanization of construction" and "reconstruction of walls". There are building construction firms such as large-scale block-assembled large slabs and large formwork cast-in-place. Beginning in 1964, new prefabricated siding buildings have been promoted nationwide. The building codes matching the prefabricated buildings were compiled. The case projects are shown in Figure 2.42, Figure 2.43 and Figure 2.44. However, due to the monotonous product, high cost and some key technical issues at that time, it was not resolved. The comprehensive benefit of construction industrialization is not high.

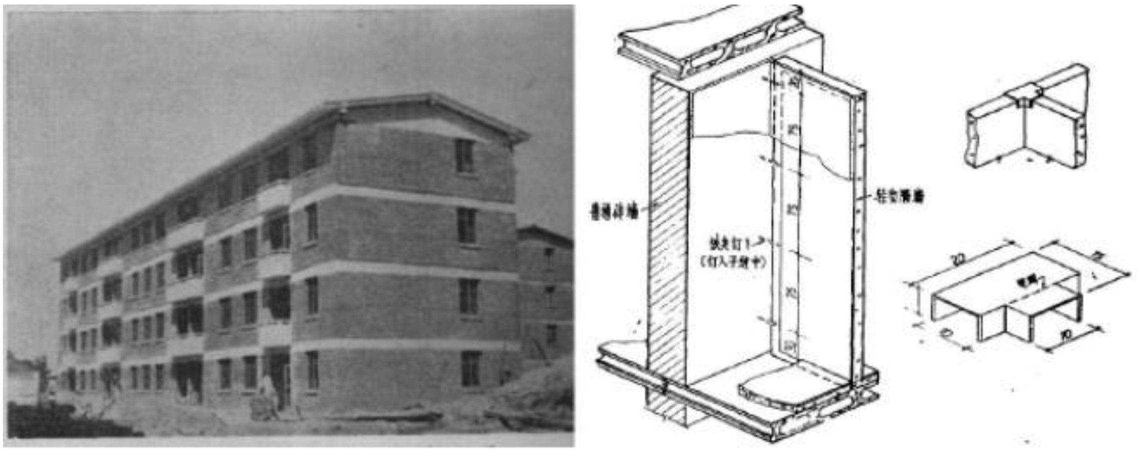


Figure 2.41. the First Prefabricated Building in China [50]

Figure 2.42. Beijing Tiantan Community under construction [50]

Figure 2.43. Large-Slabs Dormitory Building in Southwest Jiaotong University Emei Campus [50]

Figure 2.44. Residence at Nanlishi junction outside Fuxingmen, Beijing [51]

This period was promoted by the government in the form of a planned economy, focusing on the construction of building structures. Under the planned economic system at that time, building construction served the society and production was more important than life. The quality of construction only stays at the standard level of "low standard and low cost", ignoring the pursuit of individuality and beauty in residential buildings. In the 30 years of industrialization construction practice, the productivity and labor technology level are low, and the development of residential industrialization is slow, and no major progress has been made [51].

2.5.2. 1976 ~ 1990: the period of exploration

In 1976, the Tangshan earthquake occurred in China. In this earthquake, most prefabricated buildings collapsed during the earthquake, causing many casualties and property losses. This makes China's construction industry rethink the development direction of prefabricated buildings. Since then, China has successively introduced prefabricated building technologies from Yugoslavia and Japan and carried out experimental construction. At this stage, the improvement of the quality of industrialized residences mainly focused on improving internal functional spaces and improving product quality. Based on ensuring the quality of the project, systematically carry out the practice and academic research of the industrialized technology residential design methods and related theoretical systems. Through studying the mature research results of open architecture theory abroad, the standardization design work in China is also gradually carried out. The product catalog of parts has been designed and perfected, laying the foundation for the diversified design of industrialized housing. In 1988, the first residential construction project "China-Japan JICA Xiaokang Residence" was implemented in Beijing [52]. A series of research work on architectural design and construction concepts were carried out. The research on the well-off residential project in China and Japan has made important contributions to China's housing construction and improvement of the living environment. However, many problems in practice still reflect the large gap between China and developed countries in the construction of industrialized housing. The representative projects of this period are shown in Figure 2.45, Figure 2.46 and Figure 2.47.

Figure 2.45. Everest Hotel in Chengdu [50]

Figure 2.46. Beijing Capital Stadium [50]

Figure 2.47. Shijiazhuang Union Community JICA [50]

2.5.3. 1991 ~ 1999: the period of transformation

In the 1980s, housing began to implement market-based supply. The scale of housing construction was unprecedented. But this development was based on a large investment in manpower, materials, capital and land. Construction technology was still standing still. At this time, the application and development of construction industrialization was relatively slow, and only stayed in theoretical research. For example, the modulus standard was closely related to industrialization. In 1994, the technical specification for the construction of integral prestressed slab columns was published. It was not until 1995 that as China began to reflect on the abnormal development of the real estate industry at the beginning of the century and the need to realize a well-off society in China, the function and quality of residential buildings were gradually valued. Ways and means to achieve a well-off living standard have begun to be considered. Based on summing up and drawing on the experience and lessons from home and abroad, the construction industrialization was re-proposed, especially the residential construction industrialization would still be the future development direction [53]. In the mid-1990s, the Ministry of Construction formally proposed to vigorously develop construction industrialization. And through a series of measures such as pilot project construction, to speed up development. In 1996, the Ministry of Construction promulgated industry policies such as the “Outline of the Pilot Work for the Modernization of the Housing Industry” and the “Technical Development Key Points for the Pilot of the Housing Industry Modernization” in the face of the unhealthy development model of low production efficiency and high resource consumption. It proposed to change from an extensive economic growth mode to an intensive economic growth mode, adjust and improve the previously unreasonable construction industrial structure, and take residential industrialization as an important way for the future development of the residential industry [52]. In 1998, the Ministry of Construction set up a building industrialization office in accordance with the requirements of the State Council. Formalizing the promotion of the modernization of the construction industry as the government 's long-term work. On the other hand, the Ministry of Construction held a meeting and put forward the development idea of "promoting the modernization of the construction industry, improving the quality of housing, and accelerating housing construction." It aimed to solve the long-standing common problems of building quality by promoting the modernization of the construction industry, in order to improve the quality level of the building and the comprehensive benefits of building construction and promote the development of the construction industry [54].

2.5.4. 2000 ~ present: the period of experiment construction

Entering the twentieth century, China's construction supply system has undergone fundamental changes. The commercialization of housing has a huge impact on the industrialization of construction. The promotion of eco-environmental protection and green energy-saving in all fields has contributed to the transformation of building construction concepts to new industrialized construction methods [52]. Under the guidance of the idea of industrialization of construction, China has begun to transform from traditional construction methods to industrialized construction methods. The research on the industrialized design and construction technology of affordable housing has greatly promoted the healthy development of the construction industry in the right direction of industrialized construction, focusing on energy-saving ecological construction, resource recycling and green environmental protection. In August 2000, the China-US residential cooperation project was launched. This cooperative project introduces advanced residential design, parts production and construction technologies from the United States. Conducted a comprehensive and in-depth study on housing and its related standards, policies, technologies, etc., and equipped with exemplary housing. The purpose is to provide new development direction and new technical support for the development of China's housing industry. In the same year, the Construction Industrialization Promotion Center of the Ministry of Construction organized and implemented the "Construction Industry Demonstration Project" project. Based on the Internet and the database, an integrated framework was developed to establish a network management system for research, development, and construction enterprise dynamic alliance. It realizes the organic integration of the four elements of people, enterprises, management and technology, information flow and value flow in each stage of activities. The project selected Beijing Longzeyuan Community as a demonstration (Figure 2.48). At present, it has passed the national acceptance and achieved obvious results. It provides a good demonstration role for the information transformation of the traditional housing industry and future development. Beginning in 2001, national construction industrialization bases began to emerge continuously. More than 30 national construction industrialization bases, including Vanke (Figure 2.49), Qixia Construction and Shandong Wansida, have been established in order to promote and develop residential industrialization by establishing industry models and using point-and-plane promotion models. The government is also actively cooperating with financial industries such as insurance and banking. By adopting financial preferential strategies to encourage more enterprises to join the development of residential industrialization [55].

Figure 2.48. Beijing Longzeyuan Community [56]

Figure 2.49. Nanjing Vanke Shangfang Affordable Housing Project [56]

2.5.5. Development status of prefabricated buildings in China

Although China has conducted a lot of theoretical and practical explorations on the system of prefabricated buildings, it has not yet formed a complete set of general system for residential industrialization. From the perspective of construction experience, the prefabricated building system is a professional production method that integrates building components into a building system with excellent performance products. The generalized building system must meet the standardization and generalization of prefabricated structural parts, supporting products and connection technologies, so that the structural parts and node structures required by various buildings can be interchanged and used universally. Both Europe and Japan have formed their own universal building systems, such as

25 industrialized building systems in France and SI technology system in Japan. They are all industrialized building systems enforced by the state. At present, as a whole, China's construction industrialization level has improved, but the overall level is not high, especially the development of the relative parts system is relatively backward compared to foreign countries with a relatively high level of residential industrialization. According to statistics, China's residential general parts account for about 20%, while Japan's newly built residential general parts can account for about 80%. There are many manufacturers of building materials and parts in China. But most of them are based on single products. They lack technology, component integration and supporting capabilities. Building materials, equipment and building parts have not yet formed a socialized production and supply system with advanced technology, large-scale production and serial supporting. As a result, the building quality is not high, the versatility of the equipment is poor, and the performance-cost ratio is unreasonable. There is a lack of connection and coordination between building components and architecture, and between components. Assembly technology is still a low-level extensive type, basically still relying on manual operations with low technical content. Therefore, labor productivity is low, and the construction quality qualification rate is very different from developed countries. The certification of industrial components and related specifications need to be improved. There is no specific and feasible standard, and problems will occur in all aspects of plan approval, construction, acceptance and sales. In addition, compared with the construction of traditional cast-in-place buildings, the construction of prefabricated buildings has higher requirements on the technical level of construction. The extensive traditional operation mode uses simple equipment and backward technology. The construction level of workers is limited. It is difficult to achieve technological breakthroughs and development. Before migrant workers became industrial workers, their production skills were not high, and their work mobility was high, which was also the reason for the low productivity and product quality of prefabricated construction.

2.6. Summary

In chapter two, provided a comprehensive survey of the historical and current development of prefabricated buildings in different countries. Through comparative research on the development history of prefabricated buildings in different countries, it is found that the development of prefabricated buildings in various countries is based on the increase in housing demand and large-scale housing construction. Under the encouragement and guidance of government policies, research institutions and enterprises promote the development of prefabricated buildings. The prefabricated buildings in various countries has experienced almost half a century of development and has basically reached a mature and stable period. Prefabricated buildings have become one of the main methods of housing construction in developed countries.

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Chapter 3. Theories and Methodology of Life Cycle Assessment and Building Simulation

3.1. Introduction

The whole building life cycle analysis can be divided into Life Cycle Assessment (LCA) and Life Cycle Cost (LCC). LCA seeks to make an overall assessment of environmental impact. The purpose is to fully consider the input and consumption involved in the entire system, while ignoring the accidental effects between the sub-items. From the perspective of economic decision-making, LCC studies the cost-effectiveness ratio of the evaluation object [1]. LCA is a new type of environmental impact assessment technology and method system. It is a method for quantitative evaluation of resource consumption and environmental impact issues involved in the whole process from "cradle to grave". Specifically, it is a quantitative analysis of the environmental load from the various stages of raw material mining and acquisition, processing and preparation, operation and use to waste dismantling.

LCC is the total cost of the various expenses that occur during the entire life cycle of the product, including the entire process from resource extraction to processing and reprocessing to become the final product. As a special product, construction engineering also has the property of full life cycle cost. The cost covers all processes such as material acquisition, building planning, design, construction, use and maintenance after completion, demolition and recycling. LCC refers to all costs related to a product incurred during its effective use, including product design costs, manufacturing costs, procurement costs, use costs, maintenance costs, waste disposal costs, etc. As for the research concept of LCC, as early as 1950, the research process of reliability in the United States had already sprouted [2]. In the report of the US Secretary of Defense in 1962, it was revealed that at least 25% of the US defense budget in 1961 was spent on maintenance costs, and it was concluded that it is the basic idea of product development to compress maintenance costs to the minimum during the entire life cycle [3]. In June 1966, the US Department of Defense (DoD) began to formally study LCC and began to use the LCC evaluation method in 1970. That is, the concept of LCC was first proposed and used by the US DoD. The definition of LCC given by DoD is the total cost of the government to set up and obtain the system and the lifetime of the system, including the cost of development, setup, use, logistics support and scrap [4]. In 1974, an Englishman named Gordon first proposed the concept of "full life cycle engineering cost management" 3; in 1977, the American Institute of Architects published "Life Cycle Cost Analysis: A Guide for Architects", further constructing the concepts and guidelines of LCC, and making LCC begin to be used in the field of architecture 4. Entering the 1980s, LCC theory has achieved staged results with the full support of the Royal Institute of Chartered Surveyors and the extensive attention of professionals. The achievements of Orshan and Flanagan are particularly outstanding. In "Cost of Life Cycle", Orshan pointed out that in comparing the selection of construction plans, it is necessary to consider both construction costs and maintenance costs when determining the total cost of the project. Take total cost as the basis for comparison and selection of schemes and put forward relevant methods on cost models and risk estimation5. Flanagan analyzed the related theories of full life cycle cost from the perspective of engineering economics in articles such as " Life Cycle Costing the Issue Involved " 6, " Life Cycle Costing: Theory and Practice " 7 and " Life Cycle Costing for Constructing "8. It further discusses the issues of cost structure and research techniques on life cycle cost management. In addition, R. Petts and J. Brooks in "Whole life cost model and its possible applications" not only give the process of life cycle cost management, but also comprehensively explore the scope of application of LCC theory. At the same time, Kirk3, Bull4, Boussabaine5, Wübbenhorst6, Ehlen 7 and other researchers have conducted in-depth discussions on the LCC method from a series of academic works and papers.

Accurate accounting of the environmental impact of a building's entire life cycle helps to understand the composition of the building's environmental impact. It is of great significance to divide the entire life cycle into a design stage, a construction stage, a use and maintenance stage, and a dismantling, recycling, and treatment stage, and then calculate effective emission reduction measures according to the carbon emission levels of each stage. The analysis of the construction life cycle cost can quantify the construction cost from an economic perspective, which is beneficial to the optimization of the construction life cycle cost.

In this chapter, the definition, characteristics and methods of life cycle assessment are introduced. And summarizes the life cycle analysis model and its application and characteristics. The second part of this chapter will introduce the collected data sources, simulation model, and the theory of the simulation tools.

3.2. Theories and Methodology of the LCA

3.2.1. The development of LCA

The concept of LCA first appeared in the United States in the 1960s and was called Resources and Environmental Profile Analysis (REPA). It was developed based on the material flow analysis method (MFA). In 1969, the Midwest Research Institute evaluated Coca-Cola's plastic packaging. It attempts to carry out comprehensive tracking and quantitative evaluation from the initial raw material mining to waste disposal. In order to quantitatively analyze the energy consumption and raw material consumption of various materials, as well as the amount of pollution they emit during the production process. This is a recognized sign of the beginning of life cycle assessment research [5]. After the study was completed, a public report published by the US Environmental Protection Agency in 1974 proposed a series of early life cycle assessment research frameworks [6]. At the same time, some research has also begun in Europe. In 1972, British scholar Boustead calculated the total energy produced by different materials for beverage packaging, including plastic, glass, steel and aluminum, and published Handbook of Industrial Energy Analysis in 1979. In the 1980s, although the development of project cases was slow, research on methodology was gradually emerging. As various environmental problems have become increasingly apparent, global environmental awareness has generally increased, and the idea of sustainable development has become popular. The society gradually began to pay attention to the research results of LCA. LCA is developing rapidly. Based on REPA's ideas, some research and consulting organizations in Europe and the United States have developed a series of methodologies related to waste management and studied in depth the potential impact of environmental emissions and resource consumption. Based on a lot of research on the inventory analysis method, the British BOUSTEAD consulting company gradually formed a more standardized analysis method, which laid a solid theoretical foundation for the subsequent development of the BOUSTEAD model. In 1984, the Swiss Federal Material Testing and Research Laboratory carried out a study on packaging materials for the Swiss Ministry of Environment. The study used for the first time a health standard assessment system, which was later developed as the critical volume method. This research has aroused widespread concern in the international academic community and has been adopted by many studies. The laboratory established a detailed inventory database based on this theory, including production process data and energy utilization data of some important industrial sectors. In the 1990s, the rapid growth of LCA related forums and seminars [7–11] further promoted the development of related research. The large number of LCA publications [12–16] also witnessed the rapid growth of related research. At the same time, Journal of Cleaner Production, Resources, Conservation and Recycling, International Journal of LCA, Environmental Science & Technology, and Journal of Industrial Ecology, etc. also began to be published gradually as LCA-related journals. In 1991, the laboratory developed a commercial computer software, which laid an important foundation for the subsequent development of life cycle assessment methodology. In

1990, the National Society of Environmental Toxicology and Chemistry (SETAC) held the first international seminar on LCA. At this meeting, the concept of "life cycle assessment" was first proposed. On the basis of SETAC, the International Organization for Standardization (ISO) established the ISO / TC207 Environmental Management Technical Committee in October 1993. After being sorted out by the committee, IS014040 Environmental Management-Life Cycle Assessment-Principles and Framework was formally issued in 1997, which proposed the basic principles and framework of life cycle assessment methods in the form of international standards. This is conducive to the promotion and application of life cycle assessment methods around the world, marking the birth of LCA's global preliminary standards. With the joint efforts of SETAC and ISO, the international standardization of the LCA method has made significant progress, and successively launched ISO14040 ～ ISO14044 series of environmental management life cycle assessment standards. After entering this century, LCA research has made great progress. The concept of LCA has penetrated into the relevant policy concepts of the European Union, forming a so-called Integrated Product Policy (IPP) [17]. On this basis, in order to make up for the shortcomings of the ISO14040 series of standards, the European Union published the International Reference Life Cycle Data System Handbook (ILCD) [18].

The building environmental performance evaluation system of countries around the world is a concentrated expression of research results in this regard. Most of these systems belong to the comprehensive evaluation system of building environmental performance. They use a comprehensive evaluation methodology and simultaneously examine the built environment quality and built environment load [16]. BREAM in UK, LEED in US, CASBEE in Japan, and ASGB in China, etc. all fall into this category. The specific evaluation form of this type of system is basically the index scoring method. Most evaluation indexes in the system are qualitative indexes, and a few indexes are quantitative indexes. There are also some building environmental performance evaluation systems that are LCA [19], such as Athena, Eco-quantum and so on. They are based on the LCA theory and the relevant life cycle inventory database, using a fully quantitative analysis method to evaluate the building as a whole, part or parts. Such systems generally do not consider the environmental quality of buildings, only analyze the environmental load of buildings. In order to simplify the use and facilitate the promotion, many research institutions have successively developed LCA software and integrated the relevant LCI database and LCIA methods into it. Figure 3.1 lists some LCA software [20].

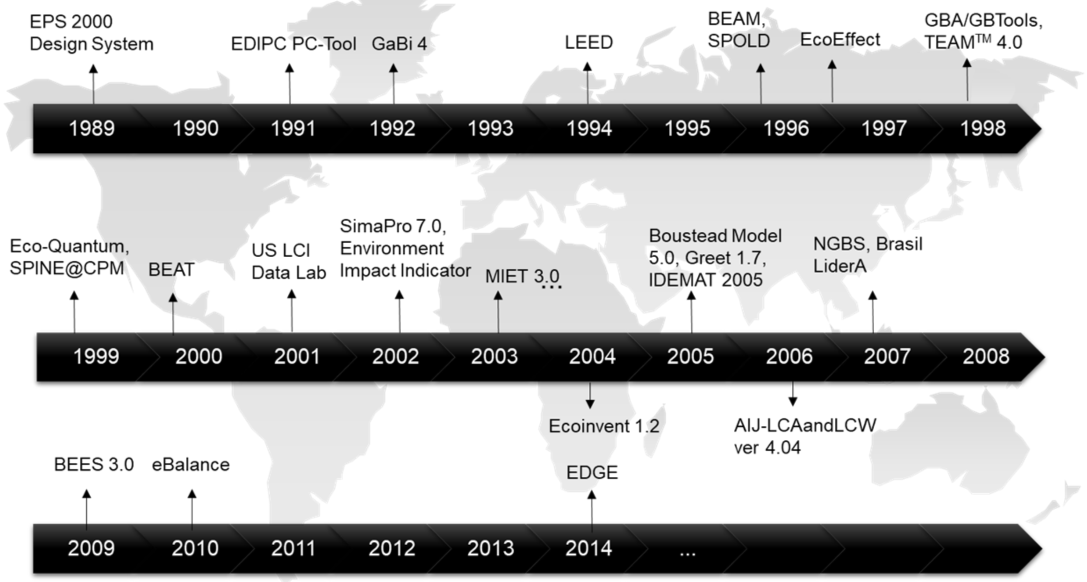


Figure 3.1.Timeline of LCA Software Development

The coverage of LCA application research is quite extensive, and almost all industrial industries can find research cases that use the LCA method to analyze product environmental performance, such as: energy, steel, nonferrous metals, automobiles, cement, plastics, fertilizers, tableware, air conditioners, etc. . Some studies take a certain system or activity as the research object, such as urban waste disposal system, transportation mode, building energy supply system, etc. Although there are still some imperfections in the LCA theory, it has penetrated all aspects of society and is playing a positive role in promoting global sustainable development.

3.2.2.The definition of LCA

LCA is currently the internationally accepted quantitative assessment method for environmental load. Different research institutions define it as follows: The International Society of Environmental Toxicology and Chemistry (SETAC) has published the definition of LCA [21]: " LCA is the process of quantifying the environmental load related to a certain product system or behavior. It first identifies and quantifies the substances, energy and emissions to the environment, and then evaluates the impact of these uses and emissions. The evaluation includes the entire life cycle of the product or behavior, including the collection and processing of raw materials, product manufacturing, product marketing, use, reuse, recycling and final disposal, and all transportation processes involved. " The definition of LCA in the international standard ISO 14040 issued in 1997 is [22] : On the basis of summarizing the world 's advanced environmental management experience, the ISO has formulated the principles and framework of life cycle assessment, pointing out Compile and evaluate the input and output and potential environmental impacts. It is a comprehensive evaluation of the social, economic and environmental benefits of the environmental impact of material and energy production during the full cycle of material component production, planning and design, construction and transportation operation and maintenance, dismantling and processing, that is, human beings defined by (ISO) The three aspects of health, resource utilization and ecological consequences. The United Nations Environment Programme (UNEP) defines LCA as [23] : "LCA is to evaluate the entire life cycle of a product system-from the extraction and processing of raw materials, to product production, packaging, marketing, Tools for use, reuse and product maintenance, up to recycling and final waste disposal-the environmental impact. "

Although the different definitions are not the same, the evaluation content and framework adopted by various agencies are basically the same: Life cycle assessment is a method for evaluating the environmental impact and resource consumption of the product from the cradle to the grave. The core feature of life cycle assessment is that it can fully reflect the environmental impact of product system functions, not limited to a single process, but is a study of environmental factors and potential impacts throughout the product life cycle process. The general model of the product system life cycle is shown in Figure 3.2.

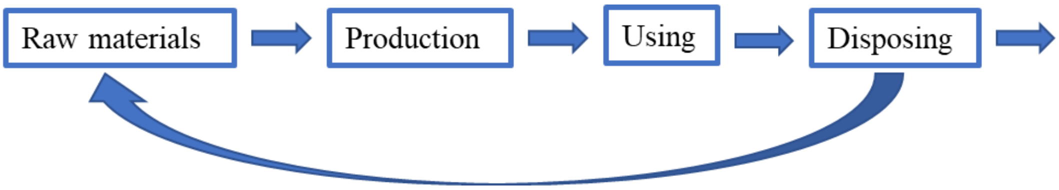


Figure 3.2. The general model of the product system life cycle

The whole life cycle theory follows the four important principles:

1). Integrated principle. The product whole process is integrated. From the manufacture of a product to its demise, it is not possible to separate any of these processes.
2). Relevance principle. Each stage of the product is closely related and restricts each other.
3). Structural principle. Different stages of different research objects have different impacts on the whole. The focus of each stage is different accordingly. Specific analysis is required when researching specific products.
4). Dynamic principle. The research object is not static but will change with the production process and product characteristics. The research method also needs to keep pace with the times and constantly make adjustments.

3.2.3.The theoretical framework of LCA

3.2.3.1.SETAC LCA

The earliest life cycle assessment framework was proposed by the Society of Environmental

Toxicology and Chemistry (SETAC). The whole life cycle includes the entire life cycle of a product, process, or activity, that is, the mining, processing, product manufacturing, transportation, and distribution of raw materials, use, reuse, maintenance, recycling, and final disposal. The LCA methodology framework proposed by SETAC summarizes the basic structure of life cycle assessment into four parts (Figure 3.3): definition of objectives and scope; inventory analysis; impact assessment and improvement assessment [24].

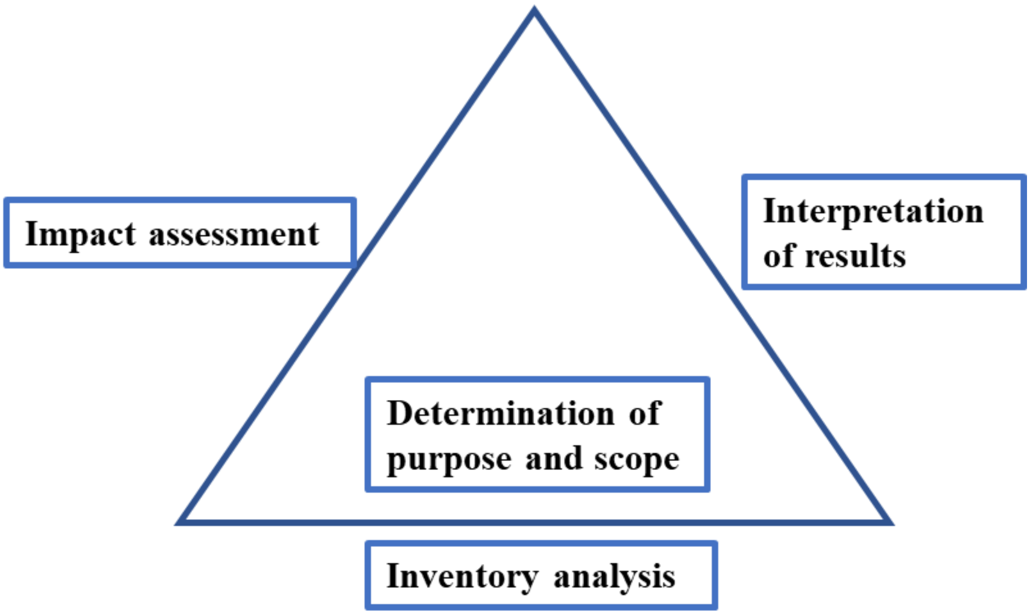


Figure 3.3. The theoretical framework of SETAC LCA [24]

3.2.3.2. ISO LCA

ISO promulgated the ISO14040 (Environmental Management-Life Cycle Assessment-Principles and Framework) standard in June 1997. ISO14040 divides the life cycle assessment into four interrelated and repeated steps: determination of purpose and scope; inventory analysis; impact evaluation and interpretation of results [22]. According to the ISO14040 standard, as shown in Figure 3.4, LCA includes (a) purpose and scope setting, (b) inventory analysis, (c) impact assessment, and (d) interpretation of results. The purpose and research scope for LCA implementation are defined in ISO14041 (released in October 1998). Inventory analysis is defined as "a component stage of life cycle assessment, which summarizes and quantifies the input and output of the target product system throughout the life cycle" (ISO14040). In other words, at each stage of the life cycle, the amount of all raw materials, energy and waste input and output are organized and quantified in the form of a list. The impact assessment standard is defined in ISO14042. Substances with environmental impacts obtained through inventory analysis can be classified as environmental impacts, such as global warming, ozone depletion, acidification, and eutrophication. Each category is listed by characteristic coefficient. In addition, damages such as human health loss, ecosystem degradation, and resource depletion are estimated by setting damage functions obtained using scientific knowledge. Finally, convert the damage to a single index through currency conversion. The standard for the interpretation of the results is defined in ISO14043. This is a process of interpreting the results of a specific environmental load or environmental impact based on the results of the impact assessment, without compromising the function of the building under consideration and linking it to improvement measures.

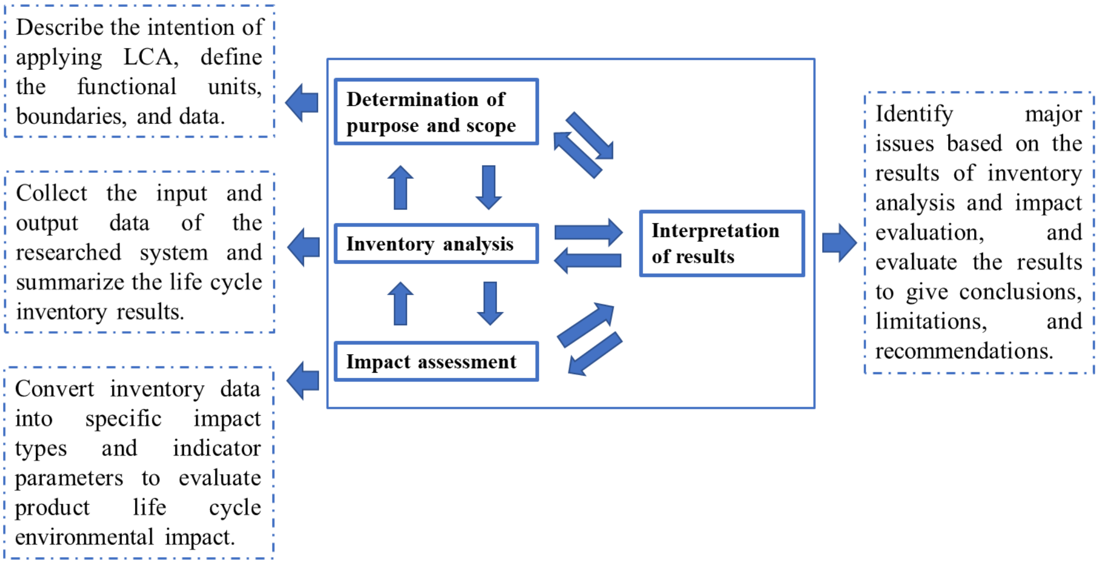


Figure 3.4. The theoretical framework of ISO LCA [22]

3.2.3.3.UNEP LCA

The LCA methodology framework proposed by UNEP also summarizes the basic structure of life cycle assessment into four parts : definition of objectives and scope; inventory analysis; impact evaluation and improvement evaluation (Figure 3.5).

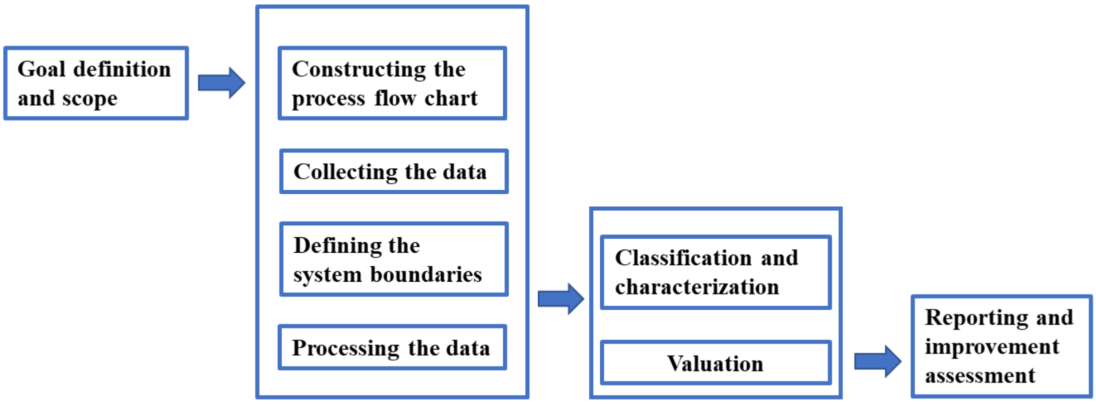


Figure 3.5.The theoretical framework of UNEP LCA [23]

3.2.4. Determination of purpose and scope

3.2.4.1.Research purposes

The determination of the research purpose is the decision-making process of the environmental information to be provided. It serves for the subsequent interpretation phase, which is to determine what questions can and cannot be answered by the results of the life cycle assessment. The purpose of the research is not absolute but is related to decision-making. Therefore, different situations will have different purposes. The purpose may be that the organization's purchasing department selects products in the market that have the least impact on the environment. Or the producer of a product should determine the stage with the most significant environmental impact in each stage of its product life cycle, in order to concentrate its energy on reducing the environmental load of the product in an all-round way. Life cycle assessment is divided into three categories according to its research purpose: conceptual, preliminary and comprehensive product life cycle assessment [5].

- Conceptual product life cycle assessment is used to solve the basic problems of product-environment system, mainly to describe the quality of environmental label products to consumers.
- Preliminary product life cycle assessment is a semi-quantitative or quantitative assessment of the environmental problems of the product. It can be used for product design, development, and internal environmental management of enterprises, and can also be used by government departments to make research on environmental issues.
- Comprehensive product life cycle assessment is a comprehensive assessment of the product environment system that requires large amounts of data. It can be used for the certification of environmental labels, the external marketing of enterprises and the formulation of government regulations.

3.2.4.2. Research scope

The determination of the scope of the study depends on the purpose of the study. The main contents of scoping include system functions, functional units, system boundaries, types of environmental impact, data requirements, assumptions, and constraints [25]. When determining the scope of the study, the following aspects should be paid attention to.

1). Research object-functional unit

The first step in scoping is to clarify the functions that the product provides to users. The object of life cycle assessment is determined by the function of the product. Only products with the same function can be compared, to ensure the fairness of the comparison of environmental impact between product systems. Functional units are quantitative descriptions of functional attributes and should be consistent with the purpose and scope of the study. The functional unit plays an important role in the comparison of environmental impact between product systems, and it is the basis of product life cycle assessment. All data collected in inventory analysis must be converted into functional units. The main purpose of establishing a functional unit is to standardize the input and output of the product system, so the functional unit needs to be clearly defined and measurable. There are three factors to consider when defining functional units: product efficiency; product life span; product quality standards. Once the functional unit is determined, the number of products that implement the corresponding function must be determined, and this quantized result is the reference stream. The reference stream is mainly used to characterize the input and output of the system.

2). Product System

The core link of the life cycle assessment is to clarify the product system, including a detailed description of the product system and drawing the boundary between the product system and the environment, and determining the individual processes related to the entire life cycle of the product system. The basic nature of a product system depends on its function, and it cannot be expressed only from the perspective of the final product. A product system is a collection of unit processes connected by an intermediate product flow that provides one or more defined functions and provides products and services for humans through the use and circulation of matter and energy. Figure 3.6 is an example of a typical building system. The product system consists of the system and the environment. The system environment provides raw materials and energy for the system while accepting products and emissions. The product system exists as an entirety, including the entire process of waste disposal from the initial raw material mining to the final product after use. However, in practice, in order to make the product list analysis feasible, certain processes must sometimes be omitted when defining the product system.

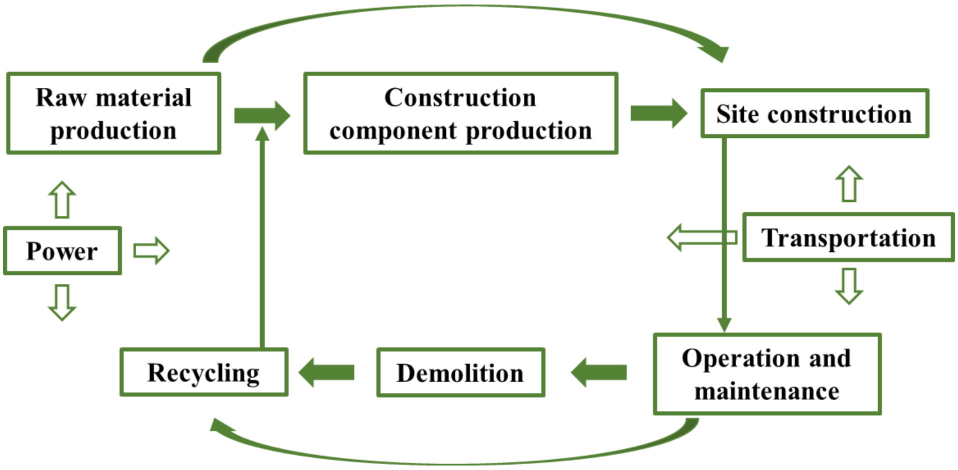


Figure 3.6. An example of a typical building system

3). evaluation standard

According to the purpose of the study, the evaluation criteria for the product system are determined by the scope of the study to ensure that the data collected by the product system during the inventory analysis phase is consistent with the selected evaluation criteria. Despite trying to use socio-economic factors and ethical factors as evaluation criteria, most studies only consider direct environmental impacts and resource consumption [26].

4). Data quality

Data quality determines the quality of the final life cycle assessment results. Data quality mainly involves time span, spatial scope (local, regional and global) and technical level. The source of the measured data and literature data should be clearly stated. The measured data should be representative and should reflect the main energy flow and material flow in the system. The main factors for data quality considerations include: [27]

- Accuracy: The degree of variability of the value of each data type.
- Integrity: In each process, the data obtained accounts for the proportion of all potentially available data.
- Representativeness: Whether the data used can accurately reflect the characteristics of the system.
- Compatibility: The methods used for qualitative evaluation are consistent.
- Repeatability: Whether other life cycle assessment practitioners can obtain the same research results based on the reported data and methods.

3.2.5.Life cycle inventory analysis

Over the past few decades, the application of LCA has gradually expanded from a single industrial product to systematic evaluation objects such as natural resource extraction, production processes, industrial parks, and various engineering projects [28,29]. The fields involved include various aspects such as energy, environment, economic evaluation and social policy [30]. In response to the continuous expansion and complexity of evaluation objects, the LCA method system is also constantly improving its own defects and developing new forms. At present, according to different system boundaries and methodological principles, there are three main types of life cycle assessment methods according to the list analysis [31]: Process Life Cycle Assessment (Process-based LCA, PLCA), Input-output Life Cycle Assessment (Input-output LCA , IO LCA) and Hybrid Life Cycle Assessment (Hybrid LCA, HLCA). These three types of LCA methods have advantages and disadvantages in analyzing and evaluating research objects of different scales. When researching specific issues, it is often necessary to use the advantages of various methods through combination.

3.2.5.1.Process life cycle assessment based on inventory analysis

Process life cycle assessment (PLCA) is the most traditional and classic life cycle assessment method. It is a bottom-up analysis method, which is mainly evaluated based on the input-output list of materials, energy and environmental emissions during the entire life cycle of product production or service. Driven by SETAC and ISO, PLCA has developed rapidly internationally and is still the mainstream life cycle assessment method [10,32,33]. PLCA is to decompose products or processes into several unit processes, based on the principle of material balance to study the exchange of substances and energy between unit processes and external systems, and finally summarize the data to obtain the environmental data of the products or processes [34].

The advantage of the PLCA method is that it considers the main processes with significant environmental impact. The results are highly targeted, accurate, and reliable, making it easy to compare products. It can accurately analyze the full life cycle environmental load of specific products or services and compare the environmental impact of different products. And can adjust the evaluation model according to the specific situation of the product or service, determine the scope and accuracy of the evaluation [35–38]. However, the PLCA method based on inventory analysis inevitably has a truncation error, that is, the accounting is incomplete. The main reason is that the division of the system boundary is often subjective, and the system boundary is not complete and consumes more time and costs [39–41]. The incomplete system boundary, also known as system truncation [39], mainly includes both horizontal truncation and vertical truncation [40]. In the process of calculating the environmental impact inventory data of the building, due to the large number of materials and services invested in the construction products, process analysis often ignores the environmental impact implied by some materials and services, resulting in lateral truncation errors. Longitudinal truncation mainly refers to that process analysis can only be carried out within a limited level of the evaluation system and cannot solve the problem of infinite extension of the system boundary, resulting in longitudinal truncation errors. In theory, the collection of complete life cycle inventory data needs to be recursively forwarded. First sort out the various input lists of the product production or service provision process, and then extend the production process of these inputs to the mining stage of ore and fossil energy. However, there are a lot of energy and material inputs in the product production process. Each input is also produced through a certain link, and sometimes there are "loops" (for example, steelmaking requires electricity, and power generation also requires steel inputs). With limited time, manpower and material resources, it is almost impossible to collect all inventory data. In fact, the production process of any product is directly or indirectly connected with various industries in the national economic system. In actual operation, PLCA often defines the system boundary at a node according to the existing data conditions and contains as much as possible the input data that is critical to product evaluation. The negligible influence on the results is excluded, so that the product evaluation can proceed smoothly [41]. However, this subjective system boundary setting often lacks scientific basis, which makes PLCA calculation results have truncation errors, and sometimes even contradictory conclusions. For example, Hocking [42] and Camo [43] each published the results of the environmental impact comparison of disposable paper cups and plastic cups in Science. But the conclusions drawn by the two are exactly the opposite. In addition, PLCA accounting can only be based on physical inputs. The process of product production and service provision based on intangible inputs such as money and labor cannot be effectively evaluated [44].

3.2.5.2.Life cycle assessment based on input and output

The input-output table is an analytical method reflecting the dependence of the quantity of input and output between various sectors of the economic system studied and created by Leontief in the 1930s [45]. This analysis method was mainly used for economic analysis in the early days. In 1970 Leontief applied input-output analysis to environmental problems and proposed the IO-LCA model [45]. As the resource and environmental problems become more and more obvious, they are gradually introduced into various fields such as natural resource development and environmental protection [46].

Unlike PLCA, IO-LCA is a top-down life cycle analysis method based on input-output tables. It first uses the input-output table to calculate the energy consumption and emission levels at the sector level, and then evaluates the environmental impact of specific products or services through the correspondence between the evaluation object and the economic sector. Input-output analysis reveals the economic and technical links between industrial sectors, which can easily trace the environmental impact implied by various materials and services that are input to products in specific sectors. In particular, the input-output model uses the economic system of a country or region as the evaluation boundary and quantifies the complete consumption relationship between departments, so it can fully account for the energy consumption and environmental impact of products or services. In addition, the input-output table reflects the flow of material and energy between various departments in the form of currency. Therefore, for the products or services of a certain sector, the use of input-output tables can analyze the indirect energy consumption and emissions caused by the production of the product or service by other industry sectors. The calculation process of the input-output life cycle evaluation model can be expressed by a matrix. First obtain the direct energy consumption and emission matrix of each department. Then it is multiplied by the direct consumption coefficient matrix (derived from the input-output table) that reflects the direct and indirect input-output relationship between various sectors. The energy consumption or environmental emission intensity of various sectors of the national economy can be obtained (representing the energy consumption or emissions per unit of monetary output of that sector) [28].

At present, there are three main forms of evaluation of products or services using the EIO-LCA method: direct department correspondence, division of product or service production processes, and division of input-output tables [28,29] (Figure 3.7). The form adopted in the accounting depends on whether the product or service has a good correspondence with the departments in the input-output table. Specifically, when the corresponding relationship between a product or service and a sector is good, the price of the product or service can be directly multiplied by the corresponding sector's energy consumption or emission factor [Figure 3.7 (a)]. When the matching relationship between the product or service and the department is not clear, it is necessary to sort out the inputs of equipment and raw materials in the production process of the product or service, and then correspond these inputs to the corresponding department to calculate and add the environmental load [Figure 3.7 (b)]. Another way to solve the non-correspondence between products and departments is to divide the existing departments or new departments to make them correspond to the products or services to be evaluated [Figure 3.7 (c)].

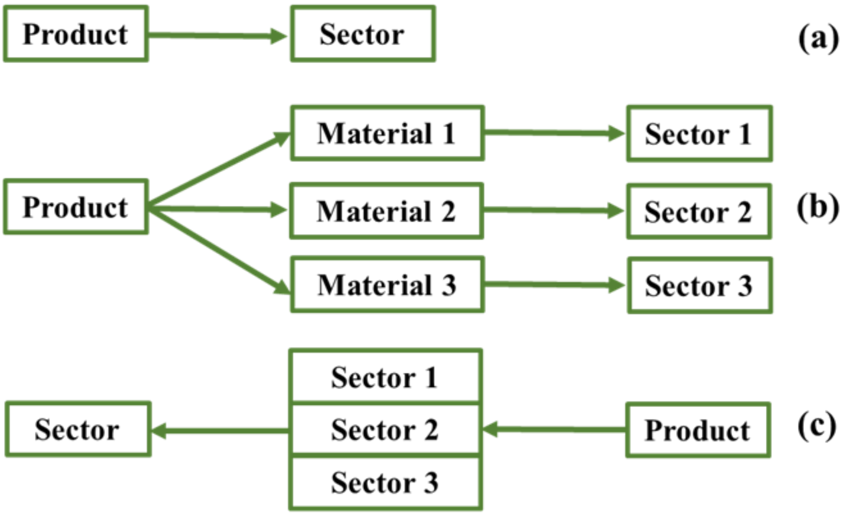


Figure 3.7. Three main forms of evaluation of products or services using the EIO-LCA method

3.2.5.3.Life cycle assessment based on input and output

Hybrid Life Cycle Assessment (Hybrid LCA, HLCA) refers to the method of combining PLCA and EIO-LCA. This method is mainly used for energy input-output analysis. For example, for the natural resource extraction process, PLCA can be used to calculate the on-site energy consumption and emissions such as transportation and mechanical energy consumption. The upstream impact of inputs such as mining equipment is calculated using EIO-LCA[47]. By combining PLCA and EIO-LCA, not only can truncation errors be eliminated, but also the specific evaluation target can be strengthened, and the use and end-of-life stages of the product can be included in the evaluation scope [48]. Since the 1990s, many HLCA methods have been introduced. The most influential methods are Tiered hybrid

LCA (TH LCA), Integrated hybrid LCA (IH LCA) and Input-Output hybrid LCA (IO-HLCA) etc. [49].

1). Tiered hybrid LCA (TH LCA)

When using TH LCA, generally PLCA method is first used to analyze the direct and downstream inputs. For example, the environmental impacts of materials transportation, on-site construction, building operation and demolition are measured using P-LCA method [50]. For the upstream natural resource extraction and equipment manufacturing, the EIO-LCA method is used for calculation. TH LCA is a list analysis method with perfect boundaries and convenient calculation. Generally, the boundary between the PLCA part and the EIO-LCA part of the TH LCA model is determined based on data availability, evaluation accuracy requirements, and human and material conditions. When TH LCA is used for accounting, inputs that are relatively clear to the process data are generally calculated directly by PLCA, while unknown inputs during the production of the target product are calculated by EIO-LCA [44]. The monetary value of these unknown inputs can be the total output value of the evaluation object minus the value of the known inputs (that is, the accounting part of PLCA). In addition, part of the process data overlaps with the input and output data, and there is a problem of double calculation. The corresponding process data needs to be removed from the input-output data [51].

2). Input-Output hybrid LCA (IO-HLCA)

The IO-HLCA method was proposed by Treloar [52], and further developed and optimized by Lenzen and Crawford[53]. The basic idea of this method is to first build the IO-LCA model to calculate the initial value, and then use the path decomposition method to find the path formed by the environmental impact. Then replace the input-output data with more reliable process data [54]. It should be noted that, like the EIO-LCA method, IOH LCA can only calculate natural resource consumption and pollution emissions during product production. The emissions at the product use and end-of-life stages should be calculated separately using PLCA or TH LCA and added to the hybrid life cycle assessment section. Therefore, IOH LCA has better applicability when evaluating objects that are used very little in product use or project operation.

3). Integrated hybrid LCA (IH LCA)

Compared with the above two hybrid life cycle assessments, IH LCA is more complicated. It represents the process data of physical quantities in the form of a technical matrix. The elements of the matrix represent the materials or energy consumed by each process unit's running time, all expressed in physical units. The input-output table is the same as the above two methods in monetary units. The combination of these two matrices is through the exchange of energy flow and material flow at the matrix boundary. For example, the upstream truncation error of the product production process is calculated through the input-output table. The downstream truncation error of the product can also be calculated from the input-output table [27]. IH LCA requires users to have a deeper understanding of the input-output table. Matrix calculations are demanding and currently have few applications. They are still at the stage of method demonstration and explanation of hypothetical cases [55].

3.2.5.4.Differences between HLCA, PLCA and EIO-LCA

The characteristics of these main types of inventory analysis methods are compared, as shown in Table 3.1. From the perspective of data requirements, data uncertainty, system boundaries, manpower and time requirements, and ease of application, the PLCA, EIO-LCA, and HLCA methods are all different. But it is difficult to determine which method has absolute superiority. Because the choice of these methods needs to consider the specific research objectives and scope, data quality and length of time. Each of these methods is affected by time lag, because input-output tables are usually published at intervals of several years. The parameters used in PLCA research are often calculated for products of other countries or many years ago, so the timeliness is not good. From a system boundary perspective, EIO-LCA and HLCA are more complete than PLCA. Because the first two methods are based on the economic input-output table, the evaluation boundary can be extended to the entire national economic system. From the perspective of data requirements, the data requirements of the PLCA method are the highest of the three methods. The evaluation results are well-targeted and the most detailed and are more suitable for specific product evaluation. But the evaluation results are incomplete, and the time and manpower and resources invested are also the most. The EIO-LCA and HLCA can be calculated more based on the environmental input-output table, so the data requirements are relatively low. However, IH LCA is an exception, because this method relies heavily on process life cycle analysis, and only the truncation error is calculated using the input-output table. Therefore, the data requirements are relatively high.

Table 3.1. Comparison

Comparison index	**P-LCA**	**IO-LCA**	**H-LCA**		
			TH LCA	**IO-HLCA**	**IH LCA**
Data Sources	Research data	Public data	Research data+ Public data	Research data+ Public data	Research data+ Public data
Results reliability	High	Normal	Depends on the ratio of process data to input-output data	High	Depends on the ratio of process data to input-output data
Research boundary	Incomplete	Complete	Complete	Complete	Complete
Time and cost	Much	Less	High proportion of process data: Much Low proportion of process data: Less	Much	High proportion of process data: Much Low proportion of process data: Less
Application convenience	Convenient	Convenient	Convenient	complex	complex
Main application range	Case study	Macro Study	Case study and Macro Study	Case study and Macro Study	Case study and Macro Study

3.3. Climate data collection and meteorological software

3.3.1. Climate data collection

Typical Meteorological Year (TMY) files was employed in the research, which are derive from Integrated Surface Database (ISD) of US National Oceanic and Atmospheric Administrations (NOAA) with hourly data through 2017. TMY files are created with the general principles from the International Weather for Energy Calculations (IWEC) Typical Meteorological Years that was published in 2001 [56].

3.3.2. Typical Meteorological Year (TMY)

Meteorological parameters are the main factors affecting the energy consumption of air conditioning. Recently, the computational dynamic simulation method has become the main technology and significant tool for building energy conservation research and practice with the scientific development of statistical reorganization theory and methods of building climate data and the mature development of computer simulation analysis technology. Nowadays, there are several software that simulate building energy consumption, such as DESIGNBUIDER, DOE2, HASP/ACLD, etc. It is necessary to input typical meteorological year data representing local outdoor climate characteristics—8760 hours of outdoor weather no matter what kind of calculation program is running. The accuracy of outdoor meteorological parameters is related to the formulation of the initial stage of building design and the accuracy of the building energy consumption simulation calculation. Typical meteorological year database used for the simulation of building energy consumption needs a lot of complete and original meteorological data to ensure the standard data produced can represent local climate laws and characteristics.

TMY is a year in which a region has typical climatic characteristics. It is selected from long-term, continuous meteorological parameters. The internationally recognized record of representing a regional climate is 30 years. The meteorological parameters include various meteorological indicators such as temperature, humidity, wind speed, solar radiation, cloud cover, and sunshine hours. The climatic characteristics of a certain region combined various meteorological parameters. The concept of a typical meteorological year is used in various energy fields. For example, in the utilization of resources such as wind power generation and solar photovoltaic heat, typical years are also required as design reference years. Due to the different emphasis of the use of meteorological resources in different fields, the selection and weighting of meteorological parameters are not the same.

TMY for building energy consumption simulation is the dry bulb temperature and dew point temperature which have the greatest impact on the building energy consumption. The most related indicator of a region is hot or cold that is the dry bulb temperature. The dew point temperature represents the local humidity and its corresponding relationship with the same time temperature, and has a direct relationship with the energy consumption of air conditioning, dehumidification and other equipment; According to the global satellite exchange data, the US Department of Energy website has provided and publicly released the typical meteorological years in various regions of the world and made important contributions to this field.

3.3.3.Climate zone and Degree Day

Climate zones in different countries are mainly defined by two parameters; temperature and moisture which are combined to create hygrothermal maps. Knowing climate zone and building accordingly is one of the basic tenants of building science. Moisture, extreme temperatures and inclement weather require completely different building techniques to ensure longevity and efficiency. When the building climate zone decided, it can be the basis for selecting techniques and materials that are safe, cost effective, and efficient to install and provide an energy efficient building envelope [57].

The most widely used method to determine climate zone is using degree days. They are essentially a simplified representation of outside air-temperature data. The degree day is a unit for calculating the heating condition or the cooling condition. Currently, the commonly used degree day is used as the number of days of heating or the number of days of cooling. The greater the number of days of heating, the lower the temperature of the brightening. The higher the degree of coldness indicates that the temperature is higher. The heating day value is zero that means the average daily temperature is higher than the heating reference temperature. Similarly, if the average daily temperature is lower than the cooling reference temperature, the cooling day is zero. Degree is a function of time integral, which can be described as the time range defined by the function, and the time varies with temperature. There are two factors that determine the interval of the function. One is to determine the reference temperature using the somatosensory temperature as a measure, and the other is to control the background climate. After determining the reference temperature, the measurement result is subtracted from the reference temperature after the temperature measurement for the whole day, and finally the difference is integrated, and the daily result is totaled. By accumulating the results over time, you can calculate the heating and cooling time during this time.

The degree day is a measure of the energy consumption of building air conditioning. When the building adopts air-conditioning is heating, the indoor and outdoor temperature difference causes the indoor to transfer heat to the outside. On the contrary, the difference causes the outdoor to transfer heat to the indoor when the air conditioner is cooling. The total number of degree day is the sum of the differences in heating or cooling during this period. The number of degree day of air conditioning directly represents the energy consumption of the building in a certain period under local climatic conditions. Therefore, the degree day is of great importance to building energy conservation, operation and air conditioning design. In energy monitoring and target planning, the total of degree day of weekly or monthly can also be used to monitor heating and cooling costs for climate-controlled buildings, and annual figures can be used to estimate future costs.

3.4. EnergyPlus and OpenStudio for building energy consumption simulation

3.4.1. Simulation model

Since 2006, DOE, the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), and Lawrence Berkeley National Laboratory (LBNL), has developed a series of reference building energy models for most common commercial buildings [58,59]. These models provide a common starting point to measure the process of energy efficiency aims for commercial and residential buildings (Table 3.2). It can be used to assess new technologies, optimized design, develop energy code, and assess building life cycle [60]. The prototype models include 16 commercial building types that represent 70% of the building stock approximately, and with three vintages (new, pre-1980, and post-1980 construction). The data sources of these models include Commercial Building Energy Consumption Survey (CBECS), ASHRAE building energy efficiency standard system, etc. OpenStudio software were integrated with the reference building models development which are published and updated regularly on the official website in an instant available EnergyPlus file format[61].

Table 3.2. DOE Prototype Building Type [59]

Building Type	**No. of Floors**	**Gross Floor Area (m^2)**
Small Office	1	511
Medium Office	3	4982
Large Office	12*	46320
Primary School	1	6871
Secondary School	2	19592
Stand-alone Retail	1	2294
Strip Mall	1	2090
Supermarket	1	4181
Quick Service Restaurant	1	232
Full-Service Restaurant	1	511
Small Hotel	4	4013
Large Hotel	6*	11345
Hospital	5*	22422
Outpatient Healthcare	3	2804
Warehouse (non-refrigerated)	1	4835
Mid-rise Apartment	4	3135

* Plus basement

The medium office building model is used for this study. The basic model is a three-story office building with a gross floor area of 4982.19m^2. Window distributed evenly along four facades with 33%

window-to-wall ratio (Figure 3.8). Floor to floor height is 3.96m, including 2.74m floor to ceiling height and 1.22m above-ceiling plenum. That glazing sill height is 1.02m. top of the window is 2.33m high with 1.31m high glass. Each floor has four perimeter zones and one core zone, accounts for 40% and 60% of total floor area respectively (Figure 3.8). The design parameters are set according to CBECS and ASHRAE 90.1 (0). Details of each thermal zone summary is listed in Appendix 1.

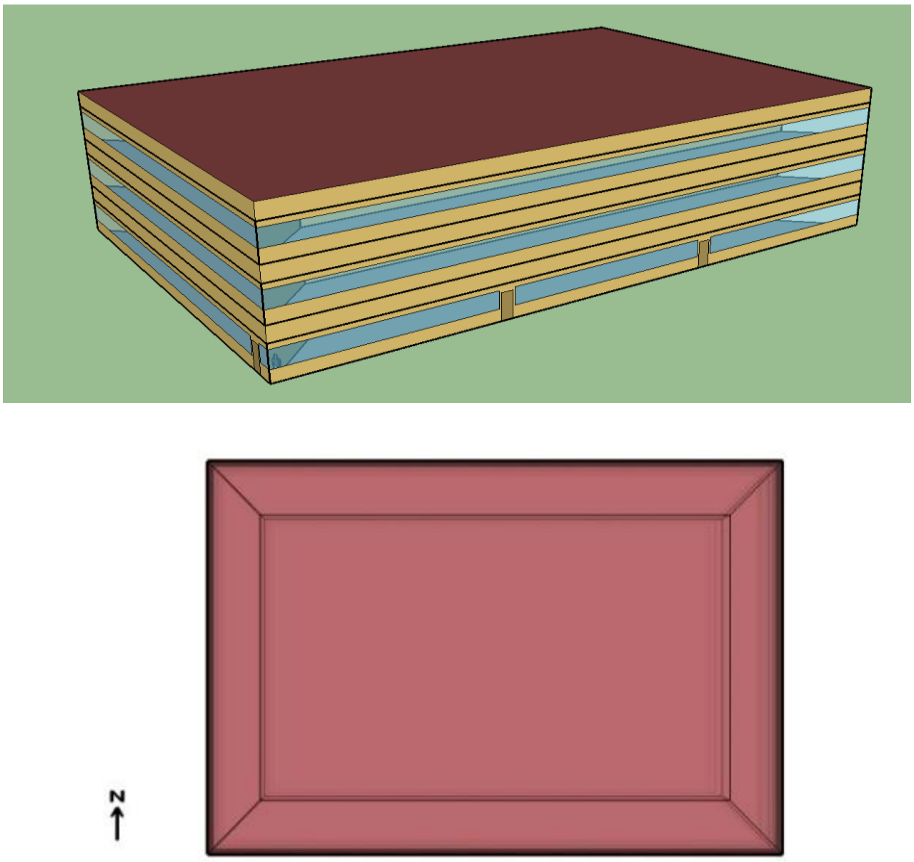


Figure 3.8. Building shape and building plan of the prototype building model.

Medium Office Prototype Building Parameters List [60]

Categories	Parameters	Value
Construction	Exterior walls	Steel-Frame Walls 10.16mm. Stucco+15.88 mm. gypsum board + wall insulation+15.88 mm. gypsum board
	Roof	Built-up roof: Roof membrane + roof insulation + metal decking
	Window	Hypothetical window with weighted U-factor and SHGC
HVAC	System	MZ VAV (multizone variable air volume)
	Heating	Furnace
	Cooling	PACU (packaged air-conditioning unit)
	Thermostat Setpoint	23.8°C cooling / 21°C heating
	Thermostat Setback	26.7°C cooling / 15.6°C heating
Internal Loads	Occupancy	18.6 m^2/person
	Outside air requirements	9.44L/s/person
	Lighting	9.69 W/ m^2
	Service Water Heating	Storage tank Natural gas
	Water temperature setpoint	60 °C

3.4.2. Energy Simulation and OpenStudio

OpenStudio is an integrated simulation that all three of the major parts, building, system, and plant, must be solved simultaneously. Building mudule simulate the impact of building envelope with the outdoor environment and indoor thermal load. System module is to simulate the air conditioning system of air transport equipment, fan coil and the related control device. The equipment module simulates refrigerating machine, boiler, cooling tower, energy storage equipment, power generation equipment, pump and other cold and hot source equipment.

3.4.3.Mathematical and Physical Analysis

The thermal load simulation in OpenStudio employed the EnergyPlus heat balanced method. The basis of the heat balance model is to guarantee the conservation of energy. The heat balance equation contains the unsteady heat transfer through the envelope and the change caused by meteorological data. It assumes that the surfaces of the room is as entities with uniform surface temperatures, uniform long- and shortwave irradiation, diffuse radiating surfaces, and one-dimensional heat conduction within [62]. Figure 3.9 shows the relationships between four distinct processes for a single opaque surface, including outside surface heat balance, the wall conduction process, the inside face heat balance, and the air heat balance.

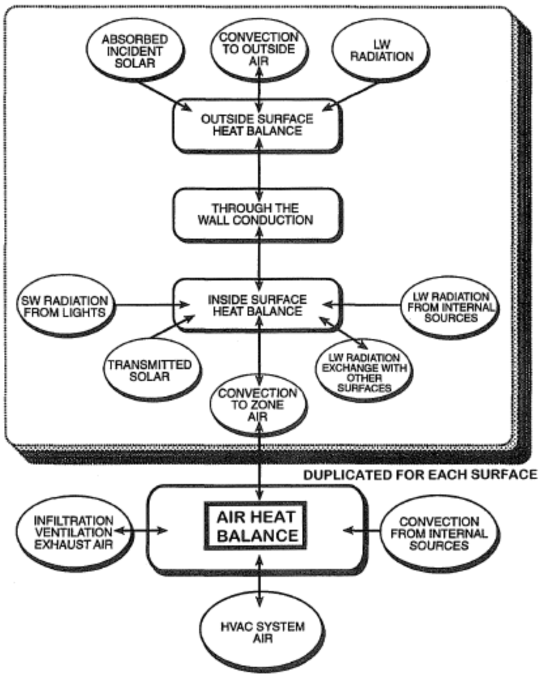


Figure 3.9. Schematic of heat balance process in a zone [62]

(1) Basis for the zone and air system integration

The EnergyPlus formulation of the solution scheme with heat balance on the zone air is:

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{sl} \dot{Q}_i + \sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys} \tag{3.1}$$

Where:

$\sum_{i=1}^{sl} \dot{Q}_i$ = sum of the convective internal loads;

$\sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z)$ = convective heat transfer from the zone surface;

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z)$ = heat transfer due to interzone air mixing;

$\dot{m}_{inf} C_p (T_\infty - T_z)$ = heat transfer due to infiltration of outside air

$\dot{Q}_{sys}$ = air systems output;

$C_z \frac{dT_z}{dt}$ = energy stored in zone air.

$$C_z = \rho_{air} C_p C_T \tag{3.2}$$

Where:

ρ_{air} = zone air density;
C_p = zone air specific heat;
C_T = sensible heat capacity multiplier.

If the air capacitance is neglected, the steady-state system output must be:

$$-\dot{Q}_{sys} = \sum_{i=1}^{sl} \dot{Q}_i + \sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) \tag{3.3}$$

(2) Conduction through the wall

The wall conduction process plays a significant role in the overall heat balance procedure because it links the outside and inside heat balance. EnergyPlus is using Conduction Transfer Functions (CTFs) to formulate the wall conduction process. The general form is shown by the following equation:

$$q''_{ki}(t) = -Z_0 T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_0 T_{O,t} + \sum_{j=1}^{nz} Y_j T_{O,t-j\delta} + \sum_{j=1}^{nq} \emptyset_j q''_{ki,t-j\delta} \tag{3.4}$$

for the inside heat flux, and

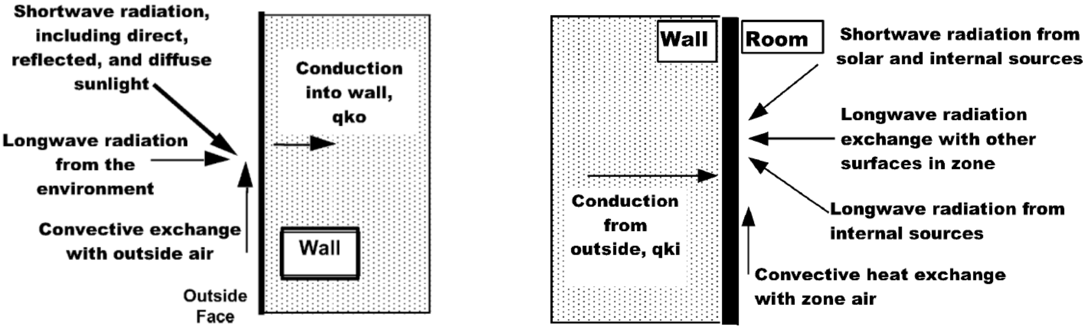
$$q''_{ko}(t) = -Y_0 T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + X_0 T_{O,t} + \sum_{j=1}^{nz} X_j T_{O,t-j\delta} + \sum_{j=1}^{nq} \emptyset_j q''_{ko,t-j\delta} \tag{3.5}$$

for the outside heat flux (q“=q/A)

Where:
X_j = outside CTF coefficient, j=0, 1, … nz;
Y_j = cross CTF coefficient, j=0, 1, … nz;
Z_j = inside CTF coefficient, j=0, 1, … nz;
$\emptyset_j$ = flux CTF coefficient, j=1, 2, … nq;
T_i = inside face temperature;
T_o = outside face temperature;
q''_{ko} = conduction heat flux on outside face;
q''_{ki} = conduction heat flux on inside face.

The subscript of the variables following the comma stands for the time period for the quantity in terms of the time step δ. The first terms in the left series have been separated from the rest so that facilitated solving for the current temperature in the solution. The terms of nz and nq depend on the wall structure.

(3) Surface heat balance process



a. Outside b. Inside

Figure 3.10. Heat Balance Control Volume Diagram

The heat balance on the outside face is:

$$q''_{\alpha sol} + q''_{LWR} + q''_{conv} - q''_{ko} = 0 \tag{3.5}$$

Where:

q''_{ko} = conduction flux into the wall, (a/A);

$q''_{\alpha sol}$ = absorbed direct and diffuse solar radiation flux;

q''_{LWR} = net longwave radiation flux exchange with the air and surroundings;

q''_{conv} = convective exchange flux with outside air.

All items in formula 1 are positive for net flux to the face except the conduction term, which is taken to be positive in the direction from outside to inside of the wall traditionally. The first three terms can be combined with an equivalent temperature of sol-air temperature.

The heat balance on the inside face is:

$$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0 \tag{3.6}$$

Where:

q''_{LWX} = net longwave radiant exchange flux between zone surfaces;

q''_{SW} = net shortwave radiation flux to surface from light;

q''_{LWS} = longwave radiation flux from equipment in zone;

q''_{ki} = conduction flux through the wall;

q''_{sol} = transmitted solar radiation flux absorbed at surface;

q''_{conv} = convective heat flux to zone air.

3.5. Summary

In this chapter, Theories and Methodology of the Study, investigated and analyzed the life cycle assessment methods, the definition of life cycle analysis methods is clarified, and the advantages and disadvantages of different methods are analyzed. At the same time, according to the characteristics of prefabricated buildings, build a life cycle model that conforms to the characteristics of prefabricated buildings. The simulation models are detailed introduce in this chapter as well. The climate data in this study are mainly employed TMY3 files which are derive from Integrated Surface Database (ISD) of US National Oceanic and Atmospheric Administrations (NOAA) with hourly data through 2017.The building energy consumption simulation among the 7 stations in Japan were estimated using EnergyPlus, a validated and physics-based BES program developed by the U.S. Department of Energy (DOE).

Appendix A. Zone summary of Medium Office Building.

Zone	**Area [m²]**	**Conditioned [Y/N]**	**Volume [m³]**	**Multipliers**	**Gross Wall Area [m²]**	**Window Glass Area [m²]**	**Lighting ² [W/m²]**	**People [m²/person]**	**Number of People**	**Plug and Process [W/m²]**
CORE_BOTTOM	953	Yes	2,859	1	0	0	9.69	20	48	8.07
TOPFLOOR_PLENUM	1,609	Yes	2,145	1	197	0	0.00	-	80	8.07
MIDFLOOR_PLENUM	1,609	Yes	2,145	1	197	0	0.00	-	80	8.07
FIRSTFLOOR_PLENUM	1,609	Yes	2,145	1	197	0	0.00	-	80	8.07
CORE_MID	953	Yes	2,859	1	0	0	9.69	20	48	8.07
CORE_TOP	953	Yes	2,859	1	0	0	9.69	20	48	8.07
PERIMETER_TOP_ZN_3	201	Yes	603	1	133	63	9.69	20	10	8.07
PERIMETER_TOP_ZN_2	127	Yes	382	1	88	42	9.69	20	6	8.07
PERIMETER_TOP_ZN_1	201	Yes	603	1	133	63	9.69	20	10	8.07
PERIMETER_TOP_ZN_4	127	Yes	382	1	88	42	9.69	20	6	8.07
PERIMETER_BOT_ZN_3	201	Yes	603	1	133	63	9.69	20	10	8.07
PERIMETER_BOT_ZN_2	127	Yes	382	1	88	42	9.69	20	6	8.07
PERIMETER_BOT_ZN_1	201	Yes	603	1	133	63	9.69	20	10	8.07
PERIMETER_BOT_ZN_4	127	Yes	382	1	88	42	9.69	20	6	8.07
PERIMETER_MID_ZN_3	201	Yes	603	1	133	63	9.69	20	10	8.07
PERIMETER_MID_ZN_2	127	Yes	382	1	88	42	9.69	20	6	8.07
PERIMETER_MID_ZN_1	201	Yes	603	1	133	63	9.69	20	10	8.07

PERIMETER_MID_ZN_4	127	Yes	382	1	88	42	9.69	20	6	8.07
TOTAL[1]	4,827		20,918		1,916	632			482.7	
AREA WEIGHTED AVERAGE							10.00	20		
1. Only volume, and gross wall area include unconditioned space.										
2. Listed lighting power density is based on applicable requirements in ASHRAE Standard 90.1-2004. The actual inputs for the models are based on appliable codes and standards										

Appendix B. Simulation cities (Japanese Stations and Climate Zone)

Country/LOCATION	Lat	Long	CZ
Kushiro	43.0408	144.193	1
Tomakomai	42.6233	141.547	2
Mutsu	41.2833	141.211	3
Sendai	38.2619	140.897	4
Hikone	35.2758	136.244	5
Chiba	35.6	140.1	6
Aburatsu	31.6	131.4	7

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Chapter 4. Environmental and Cost Performance Comparison between Prefabricated and Traditional Buildings

4.1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) [1] indicated that if the current growth rate of greenhouse gas emissions is maintained, the global average temperature will increase by 1.5 °C from 2030 to 2052, which will cause serious damage to the ecological environment. The United Nations Environment Programme (UNEP) points out that the construction industry consumes 40% of the energy, 30% of the raw materials, and 25% of the solid waste available globally and produces 36% of the total greenhouse gas (GHG) emissions [2]. The global GHG emissions from the construction industry continue to grow at an annual rate of 1.5% [3]. In developed countries, the construction industry also accounts for a high proportion of carbon emissions. Carbon emissions generated by building operation and construction account for 50%, 33%, and over 40% of the total social output in the UK, Japan, and the US, respectively [4]. Therefore, it is particularly important to understand the characteristics of in the process of construction, operation, and replacement during the life cycle of a building to reduce the environmental impact. Prefabricated buildings are buildings that use prefabricated components and prefabricated construction technology, combined with new energy-saving technology, which improves the building quality, reduces energy consumption, shortens the construction period, and saves money in the building life cycle [5–8].

Prefabricated buildings have been developed rapidly since World War II and are widely used all over the world [9]. The term used to describe "prefabricated buildings" is slightly different in various countries and regions, for example, "prefabrication", "pre-assembly", "modularization", and "off-site manufacturing" [10]. "Modular housing" is used in America [11], "prefabricated housing" in Japan and mainland China [12,13], "prefabricated buildings" in the Australia [8]; "prefabrication" in Hong Kong and Singapore [14,15], and "off-site production" in European countries [16], which refers not only to prefabs but also to elements like reinforcement structures (e.g., cages for columns) that are manufactured offside and mounted on site. The environmental impacts of prefabricated buildings and traditional cast-in-situ buildings have been compared using process models. The results showed that the GHG emissions of prefabricated buildings in the construction stage were less than those of traditional cast-in-situ buildings [17]. A similar comparative study on the consumption of materials and energy in the construction process was conducted. It showed that, compared with traditional buildings, prefabricated buildings have less wood and water usage while causing less damage to the environment and health [18]. Case studies have shown that the embodied energy content of a typical concrete frame and block construction accounts for 66% of typical concrete frame structures [19]. The thermal insulation optimization of prefabricated buildings can effectively reduce the energy consumption for heating and cooling. The durability is also better [20]. By adopting a mature recycling system, concrete waste generated from the demolition of buildings can be efficiently recycled, thereby reducing recycling costs and environmental impact [21]. The recovery rate of metallic materials and concrete is higher than that of other non-metallic materials. Non-recycled, non-metallic materials are usually shipped to landfills as waste [22]. Analysis of the carbon footprint and energy footprint of these two types of buildings showed that prefabricated buildings have reduced carbon emissions and energy consumption [23].

In the practical and theoretical fields, research on prefabricated buildings has mainly focused on the performance of building components, economic benefits, and the impact of a single stage specifically on the environment, but studies from the perspective of the whole life cycle of prefabricated buildings have been rare [24–26]. It is necessary to extend the prefabricated building study boundaries to the whole life cycle period. Prefabricated buildings have developed completely in Japan. From 1970 until now, it has developed to the fourth generation, forming a complete industrial chain from design and construction to construction operation and demolition [27]. In addition, the basic data on buildings and environment in Japan are complete, thereby providing a stable basis for the research and exploration to investigate the impact of prefabricated buildings on the environment during their life cycle [28]. Moreover, Japan has a high urbanization rate and a high level of building industrialization [29]. Therefore, the use of Japanese prefabricated buildings as the research object has significance for the development of the construction industry in other countries.

As a widely recognized environmental impact analysis tool, life cycle assessment (LCA) can be divided into two types according to the differences in the calculation process and research purposes: attribution and consequence [30,31]. The attribution LCA model is suitable for relevant studies on the impact of the building environment [15,32]. There are three kinds of mathematical model for the attribution LCA—the input-output model (I-O model), the process-based model, and the hybrid model [32,33]. The I-O model is based on the economic input and output table of a country or region, which can measure the impact on resource consumption and environment in various ranges, taking into account the sectoral dependence of related sectors of construction [34]. However, this model has homogeneity, data timeliness, and uncertainty [35]. The process-based analysis model quantifies the energy and resource usage of buildings at different stages and improves the accuracy of the results [36]. However, the data collection of this model is complex and requires high data accuracy. Meanwhile, the definition of the model's scope may also cause errors [37]. The hybrid model combines the characteristics of the process model with those of the I-O model to reduce errors [38].

The common definition of a life cycle is the entire process from the cradle to the grave, which corresponds to the scope of this paper from the design to the demolition stage. The life cycle of a prefabricated building is divided into three phases in this paper: construction, use, and demolition. The life cycle of a prefabricated building is divided into three phases—construction, use, and demolition in this paper. The purpose of this study is to analyze the energy consumption and carbon emissions of Japanese prefabricated buildings across the life cycle from the macro perspective. In view of the characteristics and limitations of the process-based model and the I-O model, the hybrid model is selected as the calculation method. In Section 2, the mixed model is used to respectively explain the supply chain activities and production processes of prefabricated buildings during different processes. In addition, the calculation methods are introduced. In Sections 3 and 4, the energy consumption and environmental impact characteristics of prefabricated buildings are analyzed under different working conditions through data collection and processing, and the advantages of prefabricated buildings are analyzed through a compassion with traditional buildings. Section 5 provides the conclusions and further describes possible measures to conserve energy and reduce environmental impacts.

4.2. Methods

4.2.1. Research Scope

The environmental impact (EI) during the life cycle of a building can be divided into three phases: the construction phase (including the design, material production, and site construction stages), the use phase (including the operation and replacement stages), and the demolition phase [39]. It can be expressed by Equation (1):

$$EI_{construction} + EI_{use} + EI_{demolition} = EI_{put}. \qquad (1)$$

where $\mathrm{EI}_{\mathrm{construction}}$, $\mathrm{EI}_{\mathrm{use}}$, and $\mathrm{EI}_{\mathrm{demolition}}$ stand for the EI from the construction phase, the use phase, and the demolition phase, respectively.

The hybrid model E_H can be presented as

$$E_{I-O} + E_P = E_H. \qquad (2)$$

where E_{I-O} is the I-O model, and E_P represents the process-based model. The I-O model is used for the analysis of production processes. The process-based model is for other processes. The two data sources are different, one is macroeconomic data for the I-O analysis, and the other is physical data for the process analysis. The I-O analysis method converts the monetary value of all relevant sectors into the final emissions at production. The process-based model converts the material usage and the corresponding environmental load into emissions for the operation and demolition phases. Figure 4.1 shows the calculation system for the LCA.

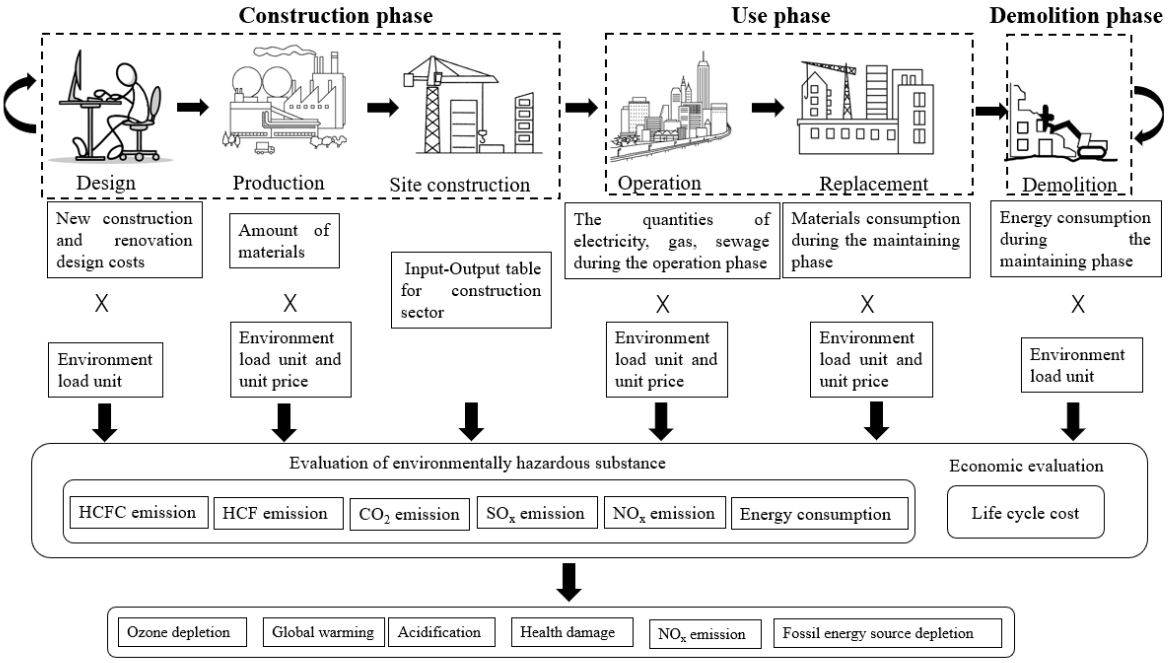

Figure 4.1 The calculation system for the life cycle assessment (LCA).

4.2.2. Input–Output Model

The input–output table is an important tool to analyze the economic and technical relationship between production sectors, which can be traced to the embodied environmental impact of a specific sector of various materials and services. In terms of the activities of various industrial sectors of the national economy, different industries are interrelated through the supply and demand of products. The development of each industry needs other industrial sectors to provide production factors for it, and the output of each industrial sector may be the input of other industrial sectors [40]. Simultaneously, a complete consumption relationship among sectors can be quantified [41]. Table 1 describes the correlations among different sectors, which can be used to calculate the intermediate consumption among sectors. The original input-output table was expanded (Table 4.1) to directly represent the material inputs of the sector, where X_i, Y_i, X_{ij}, and V_j stand for the total output, final demand, intermediate use, and value added, respectively. F_{ij} and N_j are the direct energy or carbon input of sector i because of the intermediate use and final use of sector j, respectively. $F_{f,i}$ is the total amount of direct energy or carbon input of sector i.

Table 4.1. Extended input–output table.

Output sectors		**Indirect use**				**Final demand**			**Total output**
Input sectors		**Sector 1**	**Sector 2**	**…**	**Sector n**	**Consume**	**Accumulating capital**	**Total**	
Indirect inputs	Sector 1	X_{11}	X_{12}	…	X_{1n}	II		Y_1	X_1
	Sector 2	X_{21}	X_{22}	…	X_{2n}			Y_2	X_2
	…		I					…	…
	Sector n	X_{n1}	X_{n2}	…	X_{nn}			Y_n	X_n
Value added		V_1	V_2	…	V_n		-		
Material inputs	Sector 1	F_{11}	F_{12}	…	F_{1n}		N_1		$F_{f,1}$
	Sector 2	F_{21}	F_{22}	…	F_{2n}		N_2		$F_{f,2}$
	…		IV				…		…
	Sector n	F_{n1}	F_{n2}	…	F_{nn}		N_n		$F_{f,n}$

The method has become the mainstream method used to study the environmental impact from the macro perspective (country, region, sector, etc.) [42]. Based on the "input = output" equilibrium theory, the Leontief matrix is used to represent the relationship between the total input and total output [40], which can be described as shown in Equation (3):

$$Y = (E - A) \cdot X = L \cdot X. \tag{3}$$

where $\mathrm{X} = (X_1, X_2 \cdots X_n)^{-1}$ and $\mathrm{Y} = (Y_1, Y_2 \cdots Y_n)^{-1}$ are the total input of the sector and the final demand of the sector, respectively; E is the identity matrix; $\mathrm{A} = \left[X_{ij}/X_j\right]_{n \times n}$ is the direct consumption coefficient matrix representing the value of unit i consumed by unit j; $\mathrm{L} = (L_{ij})_{n \times n}$ is the Leontief matrix.

Generally, rough division will reduce the measurement accuracy, but division that is too detailed increase the complexity of the calculation. The division in the I-O model can adopt the method of equal proportion division without changing the direct consumption coefficient of other sectors [30]. Expanding the original input-output table can directly show the material inputs of the sector. In Equation (4), X_i and Y_i are the total output and innovation value of sector I, respectively. X_{ij} is the usage amount provided by sector i to sector j, and the final demand of supply of each sector is Y_n. F_f, i represents all material emissions of sector i (including direct and indirect material emissions).

According to Table 1, the balanced equation of material consumption can be expressed as follows:

$$F_{f,\mathrm{i}} = \sum_{j=1}^{n} f_{ij} + N_i = \varepsilon\left(\sum_{j=1}^{n} X_{ij} + Y_i\right). \tag{4}$$

where $\varepsilon = [\varepsilon_i]_{n \times n}$ is a diagonal matrix that includes the emission coefficients for all sectors. Combined with Equation (3), the rewritten equation is as follows [43]:

$$\mathrm{D} = \varepsilon \cdot L^{-1} \cdot Y. \tag{5}$$

The relationship between the sectoral final material emissions and sectoral final demand is clearly expressed by Equation (5). Therefore, $\varepsilon \cdot L^{-1}$ can be simplified by the coefficient η which shows the relationship between the final material emissions and the final demand. Taking sector j for example, the relation between the total material emissions of relevant sectors in sector j and the final demand can be expressed in vertical coefficients, i.e., [38]

$$\eta_j = \sum_{i=1, \mathrm{i} \neq \mathrm{j}}^{n} \varepsilon_i \cdot L_{ij}^{-1}. \tag{6}$$

Therefore, the total substance emissions D_{oj} related to sector j are expressed by the following equation [44,45]:

$$D_{\mathrm{oj}} = \eta_j \cdot Y_j \ . \tag{7}$$

4.2.3. Process-Based Model

The operation phase can be divided into two parts: application and modification. In the process-based model, the EI of the building can be expressed as follows:

$$CE_{\mathrm{materical}} = \sum_{i=1}^{n} M_i \cdot EF_{\mathrm{mat},i}. \tag{8}$$

where i is a kind of building material, M_i is the amount of building materials (electricity, sewage, maintenance materials, etc.) used, and $M_i \cdot EF_{\mathrm{mat},i}$ is the environmental load factor of the building materials per unit of production. It should be noted that the time background and economic background should be considered in order to select the appropriate environmental load factors. The factors of materials can be found in relevant data [46].

The environmental impact during the demolishing phase is mainly related to transportation and material disposal. According to the relevant literature [36], transportation can be calculated according to the following equation:

$$CE_{demolition} = \sum_{i=1}^{n} M_i \cdot D_i \cdot EF_{trans,i}. \tag{9}$$

where D_i（km）is the distance from the demolition site i to the recycling company, M_i represents the quantity of materials, and $EF_{trans,i}$ represents the environmental load factor of the building materials of different modes of transport.

4.3. Data Collection

This study took a real-life prefabricated building case, which is located in Kitakyushu, Japan, and investigated its environmental performance. The construction life is 80 years—more information is detailed in Table 4.2. Three observation spots—including the site of the case prefabricate building, the data center that stores architectural drawings and related engineering documentation, and the prefabrication factory—were selected with the purpose of containing all related data in detail. Various measuring methods were employed for data collection. The process for each research point comprised a content evaluation of drawings and documentation of case building, for instance, the construction schedule and plan, the bill of quantities, the inventories of prefabricated components, and construction technology specifications, etc., were analyzed in detail. All of the drawings and documentation were verified and validated by all participants and experts to guarantee the data quality. Research data from the building were collected from the construction diary, records, and calculation reports (Table 4.3) [47]. The quantity and monetary value of major materials were recorded. In the operation and replacement phase, the energy consumption data were based on the actual monitoring data, which came from the operation records of related equipment. The software AIJ-LCA&LCW ver.4.04 (Architectural Institute of Japan-Life Cycle Assessment and Life Cycle Waste, 2006, Japan), developed by Architectural Institute of Japan, was used to perform data calculations. The emission factors and I-O databases for all applications were unique and consistent with the location of the building.

Table 4.2. Basic information about the prefabricated building case.

Application	**Levels above Ground**	**Floor Area (m^2)**	**Building Structure**	**Total Project Cost (JPY)**	**Project Cost (JPY/m^2)**	**Foundation Type**	**Prefabrication Rate of Structure**	**Building service life**
Public buildings	5	33500	CF	847.7x107	20.53x105	Pile	0.4	80 years

Table 4.3. Material consumption of the prefabricated building case (unit building area).

Materials	**Units**	**Quantity**	**Materials**	**Units**	**Quantity**
Reinforcing bar	kg/m^2	77.53	SBS waterproof roll	m^2/m^2	0.34
Other steel	kg/m^2	1.61	PVC downpipe	m/m^2	0.05
Shaped steel	kg/m^2	50.21	Timber formwork	t/m^2	6.17
Aluminum	t/m^2	0.54	Gypsum board	t/m^2	12.18
Precast column/beam	m^3/m^2	0.18	Carpet	m^2/m^2	0.35
Precast slab	m^2/m^2	0.82	Vinyl tile	m^2/m^2	0.65
Premixed mortar	m^3/m^2	0.02	Wallpaper	m^2/m^2	0.78
Concrete block	m^3/m^2	0.04	Door and window	m^2/m^2	0.29
Premixed concrete	m^3/m^2	0.26	Wood product	m^3/m^2	0.02
Cement	t/m^2	47.67	Glass fiber membrane	m^2/m^2	0.08
Polystyrene board (EPS)	m^2/m^2	0.63	-	-	-

In this study, "prefabricated public building" (PPB) stands for the public building using prefabrication construction investigated in this case study, and "traditional public building" (TPB) refers to the assumed public building using cast-in-situ construction.

To maintain consistency, the relevant data from different stages in the life cycle of conventional buildings were assumed based on prefabricated building materials and energy consumption. The assumption of the amount of building materials used in the traditional construction method was based on existing research findings, as shown in Table 4.4 [6,7,15,18]. PPBs use steel templates, which can be reused to produce prefabricated components. However, the wooden templates used in TPBs are disposable. In the operation stage, PPBs adopts factory prefabricated built-in thermal insulation technology with better thermal performance. According to the conclusions of Takeuchi, the energy consumption of air conditioning in prefabricated buildings can be reduced by 25% [20]. Service life is equal to the life span of the building structure. TPBs adopts the on-site construction insulation layer operation method, which has a service life of 25 years. In the demolition and recovery stage, different definitions are made for the components of the two kinds of buildings. The demolition and recovery rate of the building components and internal products of PPBs is higher than that of TPBs [6,48]. The recovery rates of different components of the two kinds of buildings were respectively assumed.

Table 4.4.Assumption of traditional public building (TPB) material consumption.

Percentage of Material Saving	**Steel**	**Concrete**	**Timber**	**Mortar**	**Heat Insulation**	**Other Decoration Materials**	**Energy Consumption**
PPB	1	1	1	1	1	1	1
TPB	1.3	1.2	1.7	1.2	1.25	1.15	1.25

4.4. Results and Discussion

Based on the scope and data defined above, the environmental impacts of the two buildings' life cycles were compared and evaluated. The results were used to compare the differences between the PPB and TPB. The characteristics of the environmental impact of the two kinds of buildings at different stages of the life cycle were evaluated in detail. In addition, the PPB with different assembly rates and with prefabricated foundation were calculated separately. The effects of the assembly rate and prefabricated foundation on the carbon emissions of the building throughout the life cycle were analyzed.

4.4.1. Material Consumption

In order to facilitate the comparison between them, the total consumption of building materials was converted into the resource unit demand (kg/m^2). Figure 4.2 illustrates the amount of input resources for the PPB and TPB. The resource consumption of PPB was found to be 3728 kg/m^2, 9.32% lower than that of TPB. Resources were saved by 9.59% in the construction process. The main reason for this is that PPBs use prefabricated components, which can effectively reduce the consumption of concrete, steel, and wood. Fabricated members use steel templets in the process of being produced, avoiding the use of wood templets. Thermal insulation is located between the layers of the PPB concrete structure without the need for mortar as a bonding material, thereby reducing mortar consumption. Additionally, building components were produced in a factory with highly accurate control, which effectively reduced the waste of concrete and steel. The resource inputs for the maintenance and replacement of the PPB components maintaining and replacement were 7.01% and 9.72% less than those of on-situ production, respectively, due to the longer product life of prefabricated components and lower material change rate in the life cycle of the PPB.

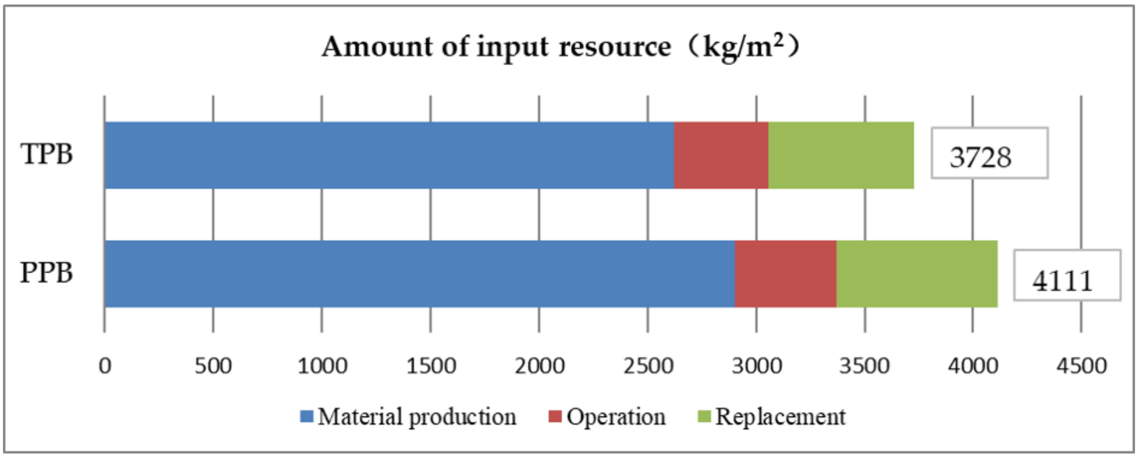

Figure 4.2 Comparison of input resource between a prefabricated public building (PPB) and a TPB.

Construction waste is produced during construction, repair, and modification and demolition. Figure

4.3 illustrates the amount of waste generated by the two types of buildings. The most waste was generated in the process of material replacement and demolition. During these two processes, building components such as doors, windows, and partition walls cannot be reused because of their inevitable destruction. The total solid waste from the PPB was found to be 2257 kg/m^2, 15.90% less than that of the TPB. The TPB generated 330 kg/m^2 and 289 kg/m^2 of solid waste during the processes of construction and replacement, which is 12.49% and 5.76% more than PPB, respectively.

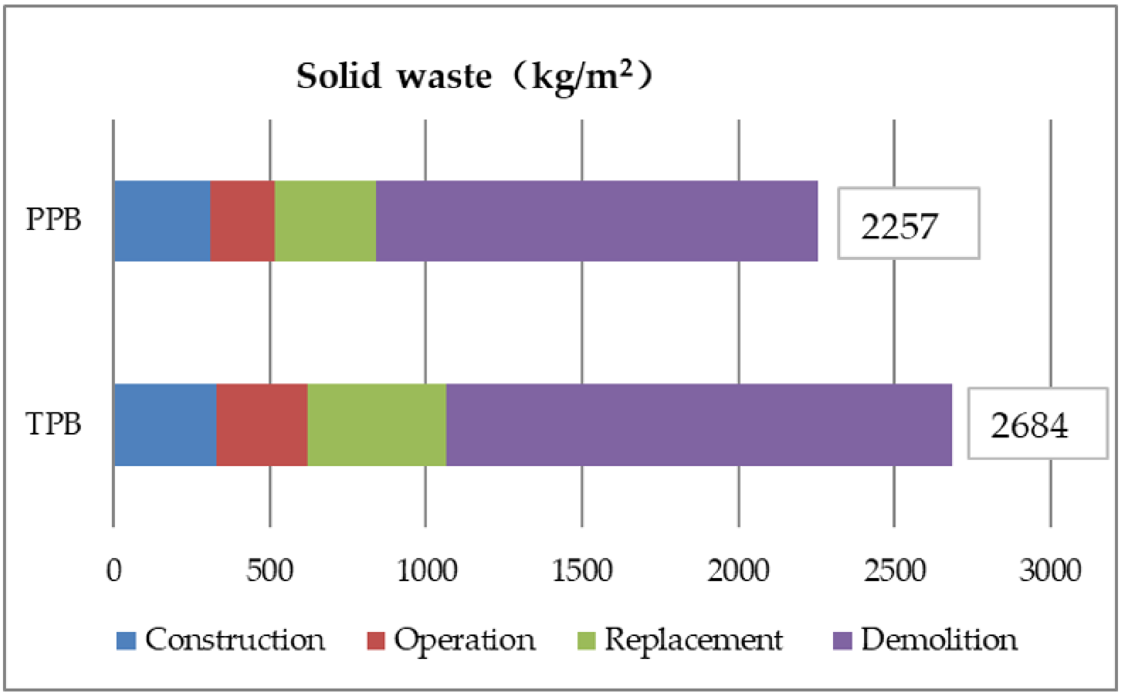

Figure 4.3 Comparison of solid waste between the PPB and TPB.

The qualified rate of building components produced in a factory is higher than that of on-site production, which reduces the generation of waste at the source. The factory is a relatively closed and stable environment with little external interference, which can reduce the loss and interference of the natural environment and human factors on materials. At the same time, the large-scale application of industrial machinery is conducive to the stable construction, thus improving the quality of products. In addition, some prefabricated components with special technologies were produced in the factory, such as insulation panels sandwiched between two layers of concrete, effectively improving the service life and reducing the renewal cycle of building components. On the contrary, due to the limitations of on-site construction, the thermal insulation layer is attached to the outer surface of the wall. Due to the poor durability, this will increase the replacement frequency of components, leading to extra construction waste. Furthermore, the organizational structure of the factory is relatively simple. On the contrary, the construction site is composed of many construction departments; the organizational structure is more complex. This also leads to the reduction of the recycling efficiency and recovery rate. Moreover, in the field investigation of this research, the factory classified and recycled most of the building materials. However, some construction materials in the construction site were disordered, making it difficult to effectively recycle some construction materials.

4.4.2. LCA-Based EI Assessment Results and Discussion

The whole process from the design to the demolition of a building will influence the environment, thus the negative impact should be reduced out at every stage of the life cycle. Using the data collected, including the quantity of building materials, energy consumption, and recovery rates of different building materials, the building impact on the environment, carbon emissions and cost during their life cycle can be calculated.

4.4.2.1.Comparison of Energy Consumption Between the PPB and TPB during their Respective Life Cycles

There is great energy saving potential in the operation phase where the most energy is consumed. Following that, energy consumption in the building material production phase is the second greatest during the life cycle. The site construction and demolition phases account for less energy than others due to their shorter durations. However, from a macro perspective, there are a huge number of construction projects every year. Correspondingly, the sum of energy consumption in these two phases will rise dramatically. The energy saving potential during these two phases should be considered as well.

Figure 4.4 summarizes the energy consumption of the two kinds of building during their life cycles. The total energy consumption of the PPB was found to be 7.54% less than that of the TPB. The PPB was shown to use less energy than the TPB at every stage. The energy saving effect in the operation stage was the most significant, reducing by 66.62 MJ/year·m^2. The PPB can reduce energy consumption by 10.93% and 7.1% in the construction phase and replacement stage, respectively. The demolition phase was shown to consume the least energy with 1.823 MJ/year·m^2, but the energy saving ratio was as high as 11.29%. The energy consumption reduction in the operation stage mainly comes from two aspects. First, energy consumption due to air-conditioning usage is lower in the PPB than in the TPB because of higher thermal insulation of the PPB. Moreover, prefabricated components have higher durability, which reduces the replacement of building components in the operation stage.

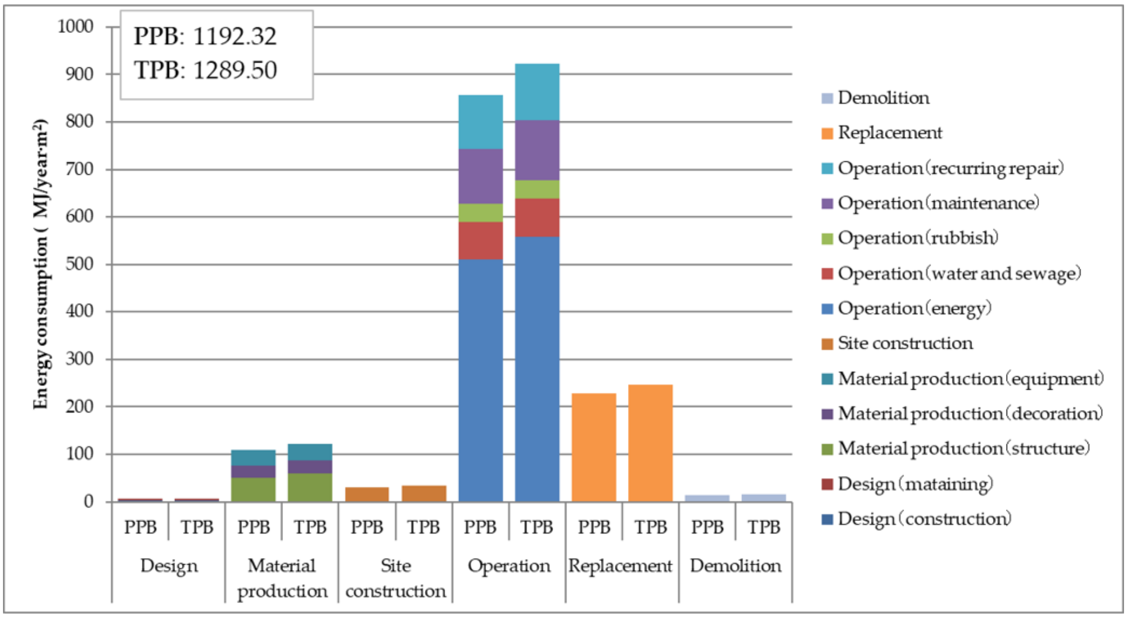

Figure 4.4 Comparison of energy consumption between the PPB and TPB during their respective life cycles.

Energy saving in the design stage is not obvious in the perspective of the building life cycle. However, during this stage, the PPB can still save 10.28% more energy than the TPB. The modular design applied, which uses fixed building modules and components and recycles components after building demolition, dramatically saves design time and money. It guides and standardizes the demolition and recycling process in the following stage. At the same time, modular design and construction improve the efficiency of supervision work, so that energy consumption is reduced in the design stage.

The energy savings of the PPB in the site construction process are mainly realized through two aspects: one is the reduction of energy consumption brought by material savings; the other is energy saving due to the improvement in equipment efficiency. The energy consumption in the site construction process mainly comes from the application of field machinery. The PPB reduces the mechanical consumption in the field construction and improves the efficiency. During the site construction process of the PPB, lifting equipment is used to lift complete building components, such as prefabricated beams, walls, floors, stairs, and so on. On the contrary, the equipment is often used to lift single building materials or building accessories, such as steel bars or formwork, in the site construction of the TPB. Therefore, the efficiency of equipment in the site construction of the PPB is improved obviously. Although the industrial production of prefabricated components increases the consumption of fuel and electricity compared with TPB, their application can avoid the installation of some building materials on the construction site, including the insulation layer, concrete, steel bars, etc. It can eliminate the requirement for concrete pump trucks and lifting machinery, thereby reducing the consumption of fuel and electricity, achieving energy saving.

4.4.2.2. Comparison of Carbon Emissions Between the PPB and TPB during their Respective Life Cycles

At every stage of the life cycle, the carbon emissions of the PPB were found to be less than those produced by the TPB (Figure 4.5). More precisely, the total carbon emissions of the PPB were 81.08 kg CO_2/year·m^2, 6.26 kg CO_2/year·m^2 (7.17%) less than the TPB. During the design, material production, and site construction phase, the emissions of the PPB were 12.623 kg·CO_2/year·m^2, 8.29% lower than the TPB. The carbon emissions of the PPB during the operation phase were reduced by the greatest amount: 4.05 kg CO_2/year·m^2. In contrast, in the replacement and demolition phase, the emissions only reduced by 1.069 kg CO2/year·m^2 in the TPB. In the process of building material production and building site construction in the PPB, carbon emissions decreased with less usage of wood formwork and fuel conservation by construction machinery.

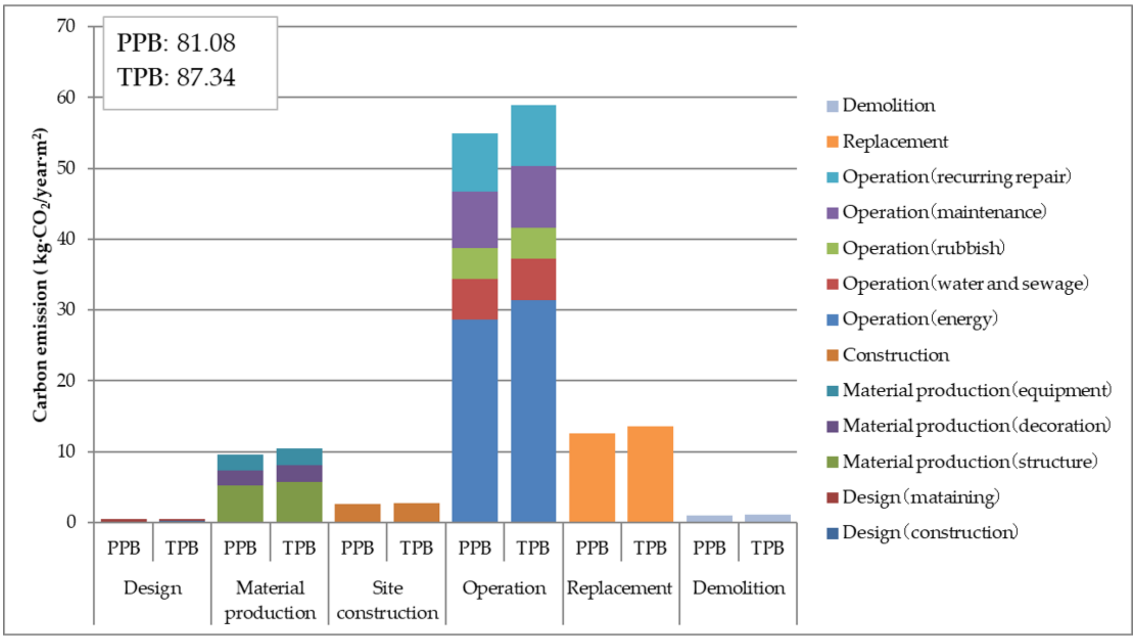

Figure 4.5Comparison of carbon emissions produced during the construction of the PPB versus TPB during their respective life cycles.

The thermal insulation panels used in the PPB reduce the energy consumption from air conditioning. Consequently, the carbon emissions were found to be reduced during the use phase (including the operation and replacement stages). Therefore, the thermal insulation performance optimization of the PPB is an efficient way to achieve energy saving carbon emission reduction during the life cycle. Increasing the thickness of the insulation layer is a general method to improve the thermal insulation performance. However, this will also lead to an increase in carbon emissions in the production stage of building materials. Therefore, when the sum of the two influencing factors reaches the minimum value, the optimal insulation thickness can be obtained to reduce carbon emissions. Different thermal climate zones have varying optimal insulation thicknesses. It is suggested that, in prefabricated production, different thicknesses of thermal insulation should be specified based on the thermal climate zone to reduce the carbon emissions throughout the life cycle of the building. Factory-made insulation walls have a long service life and low maintenance frequency. Correspondingly, from a building life cycle perspective, carbon emissions from the maintenance of prefabricated buildings are reduced.

4.4.2.3.Comparison of Cost Between the PPB and TPB during their Respective Life Cycles

It was necessary to conduct an economic analysis from the perspective of the whole life cycle. Energy saving in each stage of building is of great significance to the reduction of the environmental load. The promotion, application, and economy of energy saving technology should also be considered. Pure energy saving without considering the cost will limit the market application potential of the technology. It can be seen from the calculation results (Figure 4.6 and Figure 4.7) that the cost of the two types of building in the operation stage accounts for approximately 60% of the total throughout the life cycle, while the construction phase accounts for nearly 20% of the total. However, the material manufacture and construction should be considered comprehensively, as they are closely related to the energy consumption of the building operation stage. The PPB was found to cost less than the TPB at all stages of their life cycle, reducing the price per square meter by 10.62%. The construction phase cost was found to be reduced by 17.08% compared with that of the TPB. The use stage cost was shown to be reduced by 5.97%, and the demolition stage was found to be reduced by 16%.

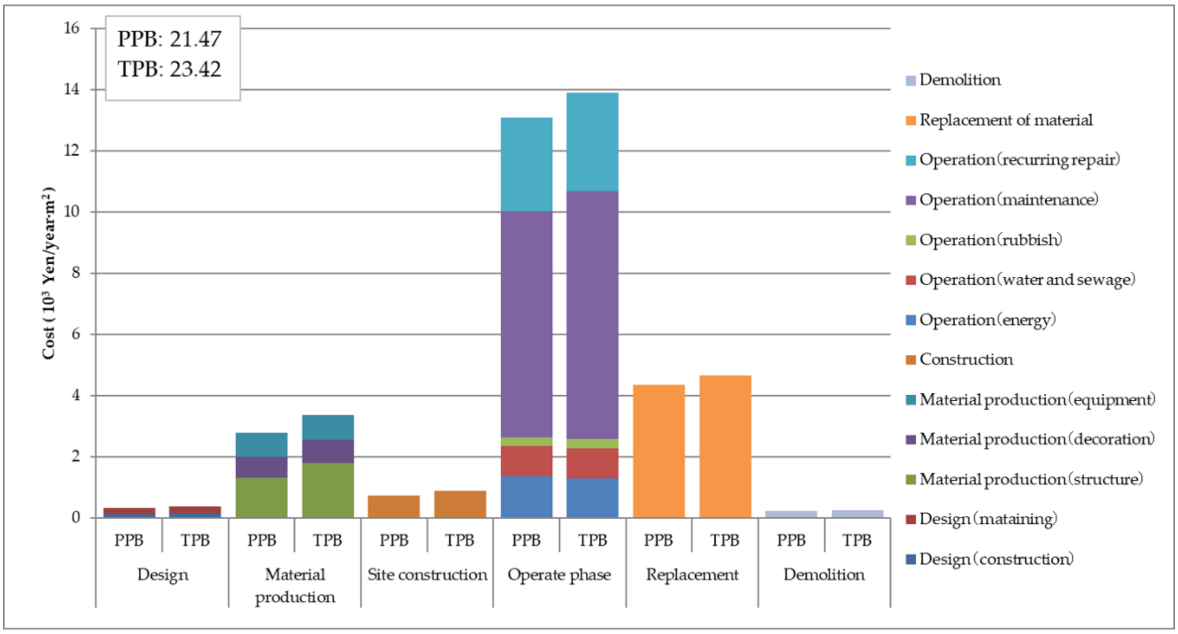

Figure 4.6 Comparison of cost between the PPB and TPB during their respective life cycles.

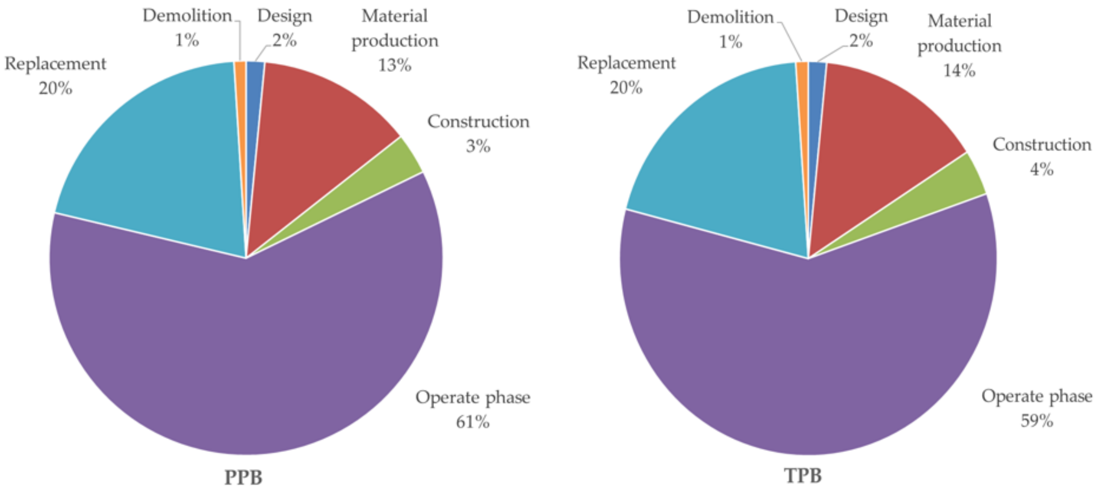

Figure 4.7 Percentage of cost at various stages of the PPB and TPB in their respective life cycles.

The reasons for this are detailed in the following evaluation. First, Japan has a complete industrial chain of prefabricated components for material production and construction. This effectively reduces the production cost of fabricated components. At the same time, the prefabricated construction method shortens the construction period and saves labor costs. In addition, the rejection rate of cast-in-situ components in field construction is higher than that of prefabricated components, which increases the input of raw materials. Furthermore, construction machinery is used more frequently than prefabricated construction, which also increases the construction cost of traditional buildings.

Generally, the quality of prefabricated components is higher than that of cast-in-situ components. Some special construction methods improve the service life of components as well, which can reduce the renewal frequency of building components in the operation and replacement stage. Moreover, the prefabricated insulation partition effectively improves the insulation performance of the building, which reduces the energy consumption in the operation process. Essentially, this indicates that the money is saved.

Finally, in the demolition stage of the building, industrial components adopt a modular design, which can be reused easily. These products are used extensively during the construction process, which means that plenty of products can be reused. In other words, it can effectively improve the bulk recycling utilization of building components. Some long-life parts—such as metal doors and windows, steel stairs, and light shields—can be reused after a simple repair. As a consequence, the recovery rate of components of the PPB is higher than those from the TPB, reducing the cost of the demolition stage. Moreover, the production of construction waste is reduced in the PPB, which means the waste treatment cost can be reduced as well.

4.4.2.4.. Comparison of Ecosystem Damage Between the PPB and TPB during their Respective Life Cycles

The performance of two kinds of building in terms of ecosystem damage is indicated in Figure 4.8. The bars under the x-axis describe the percentage of energy consumed during the material production and site construction stage, while the bars above the x-axis indicate the proportion of energy consumption during the use and demolition phase. The PPB was found to perform better at reducing global warming, acid rain, and health damage in every stage by more than 15%. This can be explained by the fact that PPB construction and operation consumes fewer materials and less energy, leading to eutrophication and global warming, for instance, materials such as steel, concrete, and wood and energy sources such as electricity and natural gas. Additionally, the emissions of harmful gases, such as CH_4, SO_2, CO_2, and NO_x, in the production of relevant materials and the use of fossil fuel is further reduced, thereby achieving the goal of reducing the environmental impact.

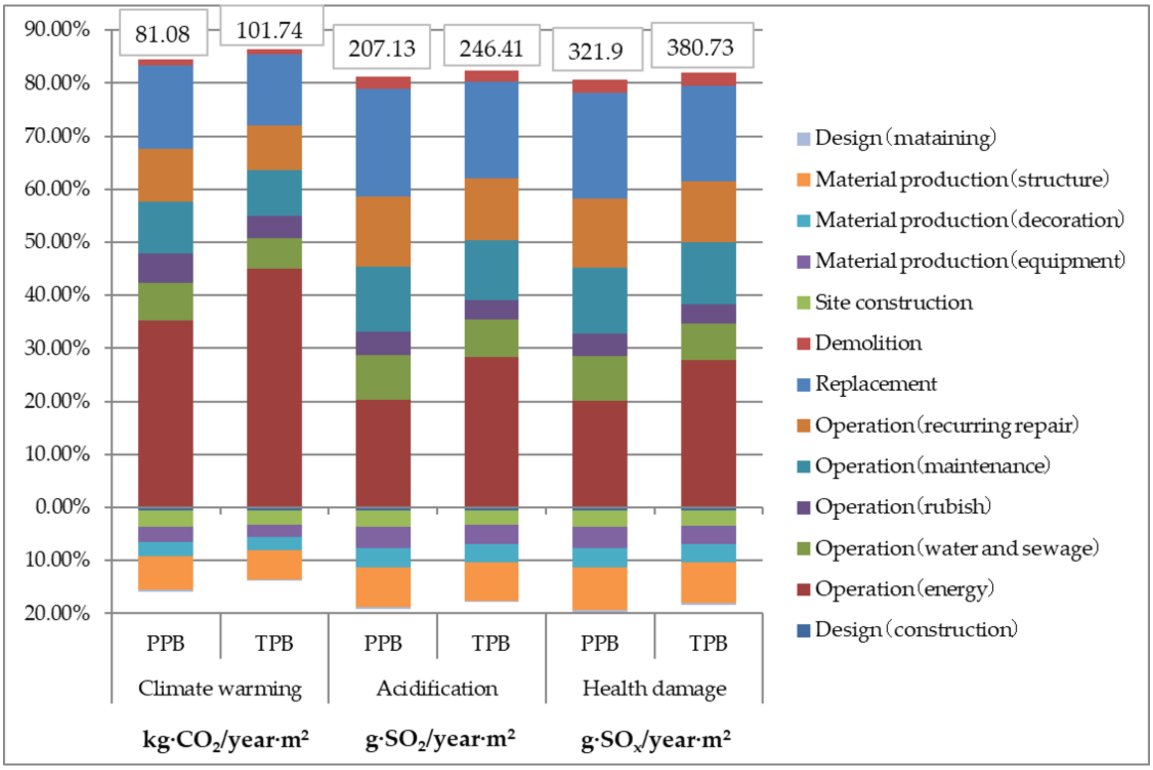

Figure 4.8 Comparison of ecosystem damage between the PPB and TPB during their respective life cycles.

4.4.2.5. Comparison of Different Assembly Rates and Prefabricated Components

The case studies conclude that the carbon emissions and cost of prefabricated buildings are superior to those of cast-in-situ buildings. Accordingly, the impact of the assembly rate on the carbon emissions of prefabricated buildings was analyzed from the perspectives of carbon emissions and economy. Most previous research on prefabricated buildings has focused on building components on the ground but has rarely involved prefabricated pile foundations. Thus, further analyses of the impact of prefabricated pile foundations on carbon emissions were conducted. The influences of structures with different assembly rates (Cases 1–4) and prefabricated pile foundations (Case 5) on the carbon emissions of PPB during the life cycle are indicated in Figure 4.9 and Figure 4.10. As we can see from the bar charts, the carbon emissions of prefabricated buildings decrease when the assembly rate rises, bottoming out when the assembly rate is 60%. Then, the emissions increase generally when the assembly rate is added. This can be explained by the following three aspects. The first point with respect to this is that the main body of the building structure is basically formed when the prefabrication rate of the structure exceeds 60%. After this, increasing the assembly rate cannot effectively reduce the use of wood formwork.

Second, as the rate of assembly goes up, some special shapes and structures with fewer applications need to be prefabricated in factories, which will increase the carbon emissions as well. This is because, during the prefabrication process of these components, the reuse ratio of the steel template is not obvious, and the production processing duration of these components is longer. Besides, the particularity of these components also causes a reduction in production efficiency, resulting in the waste of materials and excessive energy consumption in the production process.

Finally, in the site construction stage, when some special-shaped components (such as special-shaped beams and t-shaped floor slabs) are assembled on site, the construction difficulty will increase the working hours and mechanical energy consumption required, leading to an increase in carbon emissions as well.

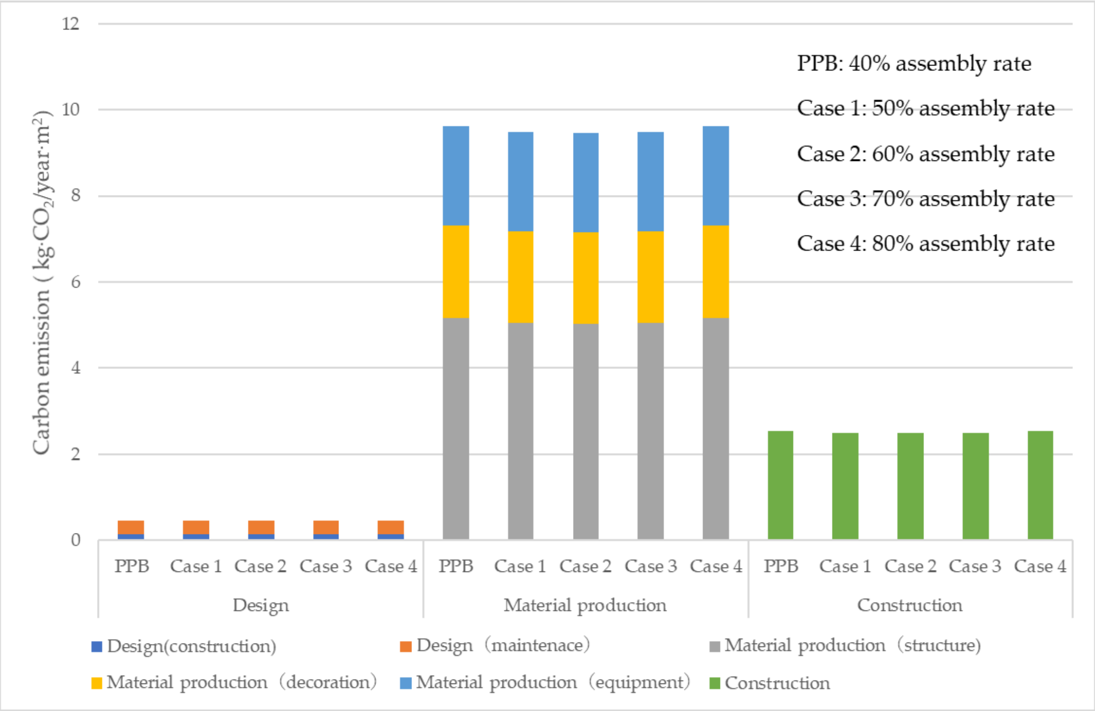

Figure 4.9 Carbon emissions of different assembly rates.

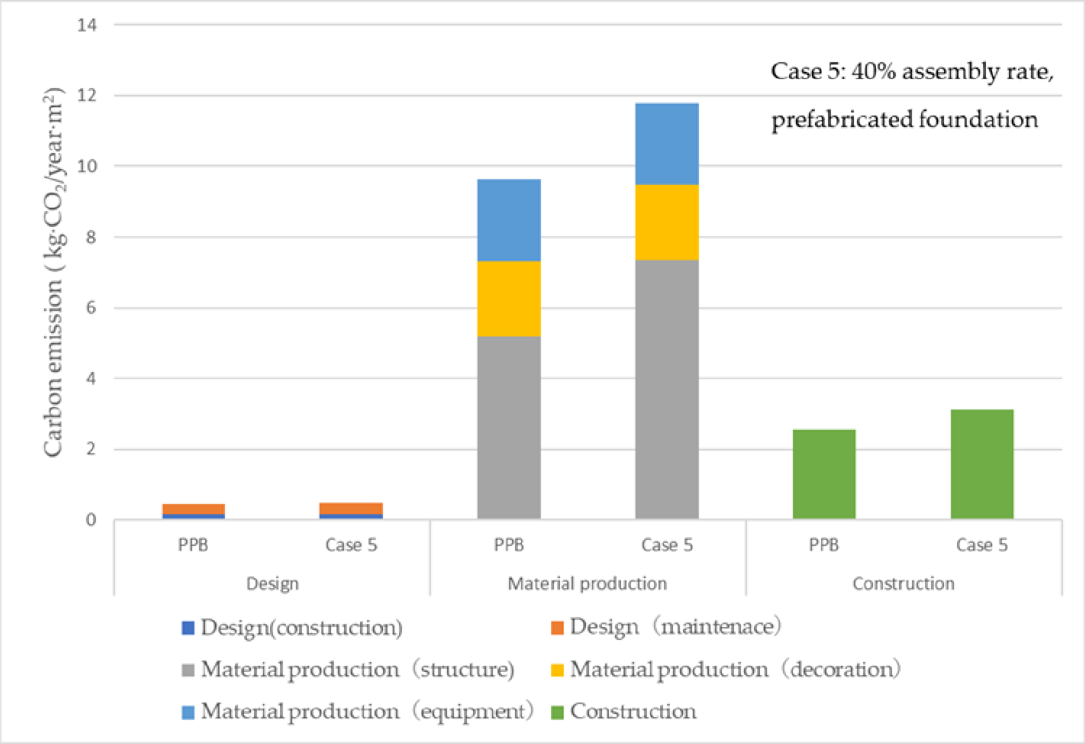

Figure 4.10 Comparison of carbon emission between the PPB and PPB with prefabricated foundations.

The relationship between the cost of prefabricated buildings and the assembly rate shows a similar trend to that shown in Figure 4.11. More specifically, the cost of prefabricated buildings drops firstly, reaching the lowest value when the assembly rate is 60%. After that, an upward trend is shown as the assembly rate increases. It is evident that, with less usage of some building components, the production cost of the components in the prefabrication production process rises significantly. Moreover, the construction cost is greater.

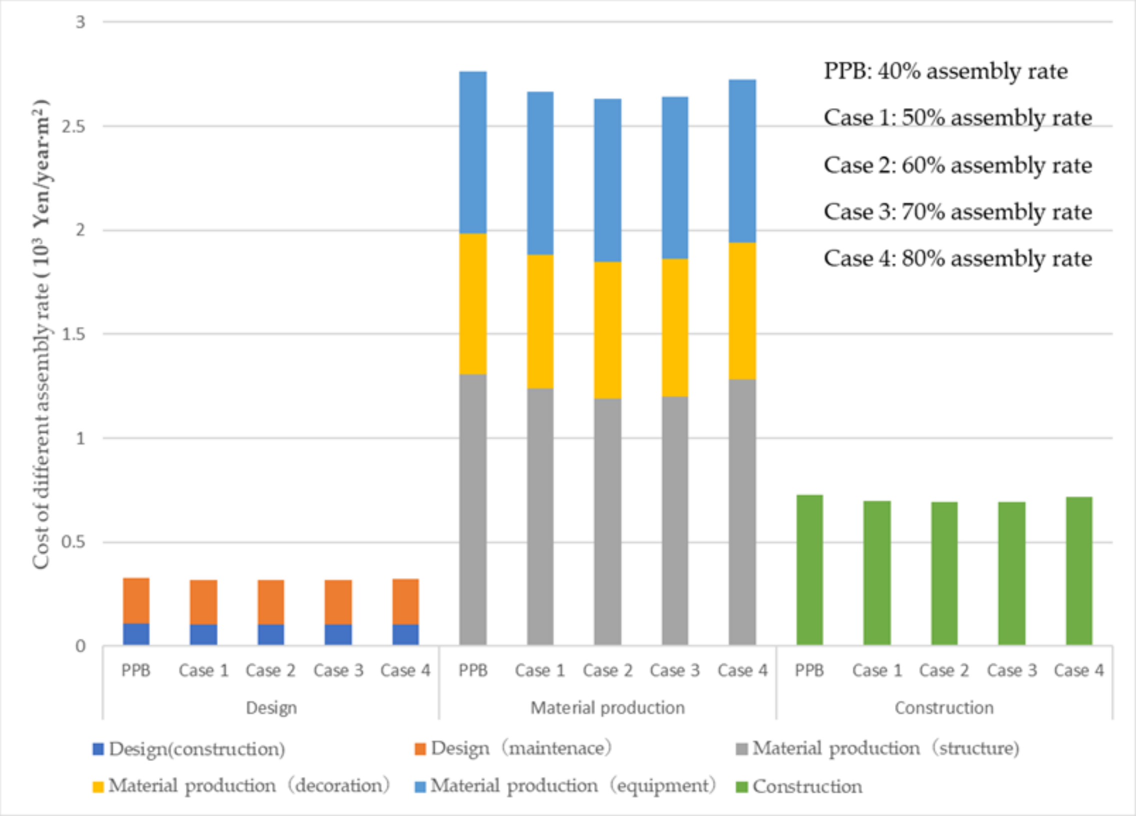

Figure 4.11 Cost of different assembly rates.

The comparative study (Figure 4.12) of the PPB and case 5 outlines that prefabricated pile foundations increase the carbon emissions of component manufacturing and construction dramatically. The reason for this is that there is a small number of building foundations with special shapes and large volume employed that make the material utilization rate of the prefabricated component production process lower, and the production cycle longer. For example, the steel formwork of prefabricated pile foundation has poor versatility, thereby increasing the consumption of steel. Steel is considered to have a major environmental impact factor, of which the impact occurs during the production and processing. In addition, it has a considerable impact on resource depletion and harmful gas emissions. Consequently, the use of prefabricated piles will increase the carbon emissions of buildings obviously. In the site construction stage, compared with cast-in-situ foundations, the use of prefabricated foundations requires more hoisting equipment to be employed. Furthermore, the precast foundation is not convenient for construction due to the high accuracy requirement of foundation positioning in construction, which increases the construction time and leads to an increase in carbon emissions in the construction stage.

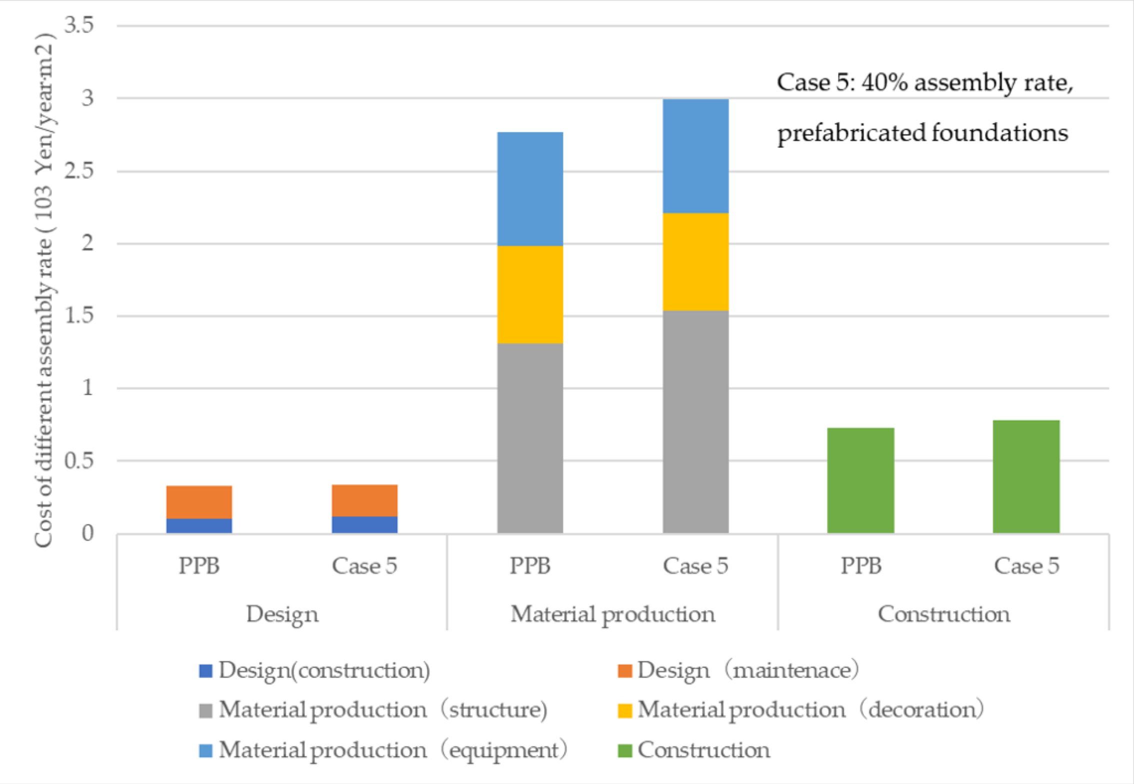

Figure 4.12 Comparison of cost between the PPB and PPB with prefabricated foundations.

4.5. Summary

This study analyzed the impact of each stage of the life cycle of prefabricated buildings on the environment based on a hybrid model. The application of the model was based on existing data to guarantee the integrity of the system boundary and the accuracy of the calculation results. In the case study, the influences of prefabricated buildings and traditional cast-in-situ buildings on the environment during the life cycle were compared. Moreover, the carbon emissions of prefabricated buildings with prefabricated pile foundations and different assembly rates were studied.

Compared with the TPB, the PPB has a reduced EI at all stages. The most significant energy consumption reduction was found to occur in the operation stage, 66.62 MJ/year·m^2, due to factory-prefabricated insulation, which improves the thermal performance and durability of the walls. The energy saving effect during the construction phase was also shown to be obvious: 17.94 MJ/year·m^2. Although the energy saving in the demolition phase was found to be the least with 1.823 MJ/year·m^2, the energy saving ratio was as high as 11.29%. During the construction phase, the use of wood formwork was significantly reduced by using prefabricated components. The consumption of materials at the construction site was also reduced. The PPB was shown to have reduced carbon emissions and energy usage by 7.17% and 7.54%, respectively. Prefabricated buildings also showed higher recycling rates than traditional buildings. The performance of ecosystem damage of the PPB was found to be better than that of the TPB, which can reduce global warming, acid rain, and health damage by 15%.

The analysis of buildings with different assembly rates indicated that the carbon emissions of PPB will increase and then decrease as the assembly rate increases. The assembly rate has the best improvement effect on carbon emissions during the construction process and has little impact on the operation and design stage. With the assembly rate rising gradually, the carbon emissions and cost of prefabricated buildings drops, bottoming out when the assembly rate is 60%. After that, there is an upward trend as the assembly rate increases. The prefabricated pile foundation is not suitable for fabricated components, which will significantly increase the carbon emissions and cost during the construction phase. Therefore, it is suggested that the cast-in-situ construction method should be adopted for the building foundations.

The use of prefabricated buildings in Japan effectively reduces the EI and energy consumption. The results are based on Japan's construction industry structure and social production level, which can help recognized the current prefabricated buildings development in Japan. The successful construction experience could provide useful information and guidance for other countries. This paper concluded various environment performance improvement potential in different building construction phase, which can help to make targeted measures to implement and promote prefabrication technologies for specific phase. The comparison of prefabricated buildings with different assembly rates points out that an excessively high assembly rate will not decrease the carbon emissions and energy consumption of the building, which remind some countries where prefabricated buildings development are just in its infancy that do not blindly seek for excessively high assembly rates.

In the initial stage of prefabricated building development, due to the incomplete supporting industry, the energy consumption of units for the prefabricated component production process may be increased. Prefabricated building development also faces many challenges. It requires high precision in the manufacture of components, which requires excellent ability of workers and strict management of prefabricated factories. The construction duration will be delayed if the prefabs are damaged during lifting or transport. Generally, prefabricated factories have to be close to the construction site to provide convenience for transportation. The durability and safety of prefabricated buildings depends on the assembly of prefabricated components, which also requires strict management of the construction sites and professions of workers. Therefore, the prefabricated building and traditional cast-in-situ building methods still coexist. Multiple factors are considered when deciding which type of building is appropriate. It is suggested that experienced and mature design companies and prefabricated parts from manufacturers are considered in the early stage of the industry’s development, which will help to improve their application. Considering the characteristics of carbon emissions during the life cycle of Japanese prefabricated buildings, it is necessary to give priority to prefabricated components of walls to improve the thermal insulation performance of buildings, which can significantly reduce the carbon emissions during the life cycle of buildings.

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Chapter 5. Environmental Performance of Envelope Insulation in Prefabricated Building

5.1. Introduction

In recent years, the concentration of greenhouse gases has continued to increase. It is expected that by 2052, the global temperature will increase by an average of 1.5 ° C [1]. Therefore, the realization of low-carbon society and recycling society has become the focus of future development. The Japanese government plans to reduce carbon dioxide emissions by 2020 by 15% from 2005 as a short-term goal, and by 2050 by 80% as a long-term goal. In Japan, 40% of total carbon dioxide emissions are attributed to the construction industry [2]. It is particularly important for the construction industry to save energy and reduce carbon emissions. In order to achieve this goal, prefabricated buildings and external thermal insulation technology based on prefabricated buildings are widely used. Prefabricated concrete building is a kind of building that is assembled into a whole by transporting various parts of a concrete structure made in advance in a specific factory to the site. Compared with cast-in-place concrete buildings, prefabricated concrete buildings can save building materials and perform well in terms of quality, and can effectively reduce the generation of waste during construction and reduce carbon emissions. The prefabricated thermal insulation system based on prefabricated buildings not only meets the earthquake resistance and fire resistance of the building, but also has good thermal insulation and heat storage performance. At the same time, it can prevent condensation and effectively reduce energy consumption and carbon emissions during the operation phase Regarding the thermal insulation system of prefabricated buildings, most of the current research focuses on the analysis of energy consumption and carbon emissions in a certain stage, such as the construction stage and the operation stage, which are relatively limited. Therefore, it is necessary to compare the energy consumption and carbon emissions of the prefabricated concrete building insulation system and the traditional cast-in-place concrete building insulation system from the entire life cycle.

LCA is widely used to quantify and evaluate the environmental load of a product during its entire life cycle, including the collection, processing, product manufacturing, product sales, use, recycling, recycling and final disposal of raw materials, and all transportation processes involved. The definition and connotation of the life cycle of construction products are clear. It is roughly divided into material extraction and production, material transportation, construction and installation, operation and maintenance, and dismantling and recycling. There are many studies on the life cycle of building materials and buildings. These studies are analyzed from the perspective of environmental impact and economy. Guan (2007) analyzed life cycle environmental, economic and social impacts of wood and aluminum doors and windows using life cycle analysis methods [3]. Van Den Heede, et al. (2012) constructed an impact assessment model to compare and analyze the physicochemical environmental impact of traditional concrete and "green" concrete [4]. Li et al. (2014) proposed to measure the environmental impact of the construction process and conduct impact assessment from the aspects of ecosystem destruction, resource consumption and health damage, based on the principle of LCA, combining the construction plan and the work of the project structural decomposition method [5]. Wang, Inge Blom et al. conducted an environmental impact assessment of the use and maintenance of a residential heating and ventilation system in the Netherlands during the life cycle [6]. It was found that although heat pumps have been regarded as sustainable systems because they extract energy from renewable energy sources, the environmental impact it brings is not less than that of gas boilers. Oscar et al. conducted a life cycle assessment of two houses located in developed countries (Spain) and developing countries (Colombia) [7]. The results show that the proportion of energy consumption and environmental impact of Colombian residences during the use phase is lower than that of Spain. This is not only because of the different climatic conditions of the two countries, but also because of their different living habits and economic levels. Although life cycle assessment still faces some problems (such as truncation error and integrity of boundary conditions), it is still an effective evaluation tool.

In this chapter, the life cycle model of thermal insulation system for prefabricated concrete buildings and cast-in-place concrete buildings is established. Based on the unit energy consumption and carbon emission factors of materials obtained from the industry association table and related literature, the energy consumption and carbon emissions of the two model life cycles are calculated. Clarify the characteristics of energy consumption and carbon emissions in each stage of the two models.

5.2.Methodology

5.2.1. Research scope

This study compares the energy consumption and carbon emissions of the thermal insulation system of assembled concrete buildings and the thermal insulation system of cast-in-place concrete buildings. The system consists of two parts: wall and roof. The life cycle of the thermal insulation system is divided into three stages, namely the material production stage, the construction stage, the disintegration and the waste recycling stage. The energy consumption during the operation phase of the building is within the life cycle of the building and is not included in the life cycle of the thermal insulation system. Waste recycling includes waste generated during construction and demolation. The life cycle of the thermal insulation system can be expressed by the following formula:

$$\boldsymbol{S_{MAT}} + \boldsymbol{S_{PRO}} + \boldsymbol{S_{DEM}} = \boldsymbol{S_{LC}} \tag{5.1}$$

In the formula, $\boldsymbol{S_{MAT}}$, $\boldsymbol{S_{PRO}}$, $\boldsymbol{S_{DEM}}$, and $\boldsymbol{S_{LC}}$ respectively represent the material production stage, construction stage, and disassembly and waste recovery stage. To define the direct and indirect environmental impacts of thermal insulation systems, the life cycle stages of the two thermal insulation systems are shown in the Figure 5.1.

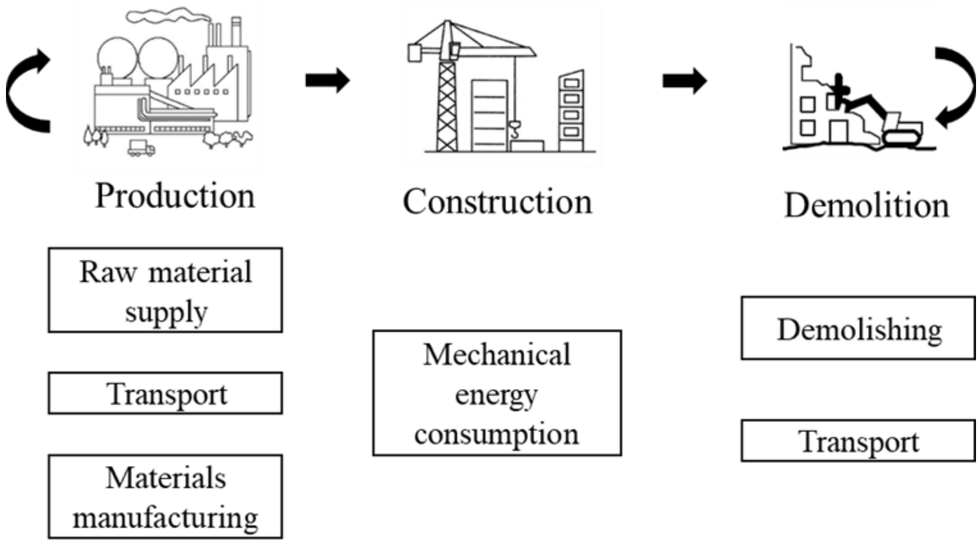

Figure 5.1.The life cycles system for the envelope insulation

The specific construction methods of the wall insulation system and the roof insulation system are shown in the Figure 5.2 and Figure 5.3. Prefabricated concrete wall insulation adopts external thermal insulation method. The wall is prefabricated by the factory. The thermal insulation of the cast-in-place concrete building wall adopts the traditional Japanese thermal insulation and is produced by the construction site. The roof insulation of both adopts the same construction method. The difference is that prefabricated buildings use factory prefabricated components, and cast-in-place concrete buildings use components made on site.

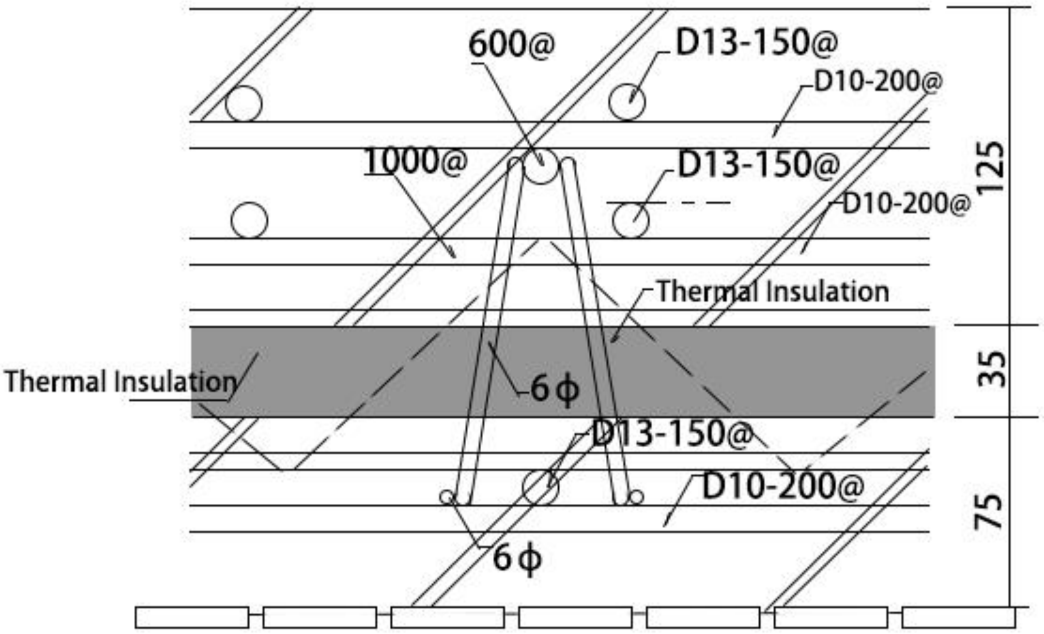

Figure 5.2.Wall insulation structure

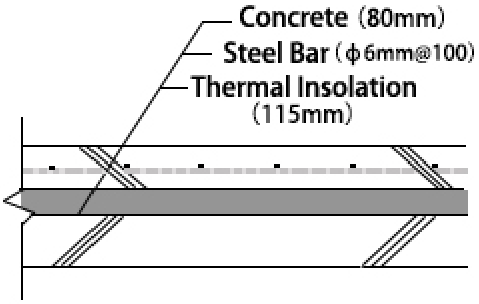

Figure 5.3. Roof insulation structure

5.2.2. Material manufacturing

The carbon emissions and energy consumption at this stage are mainly obtained from various raw materials such as cement, gravel, concrete, steel bars, and assembled thermal insulation wall components, as well as electricity, coal, gas, fuel oil and other energy consumed in the production process. The carbon emissions and energy consumption of fabricated thermal insulation walls in the manufacturing process come from two parts. One part comes from raw materials such as cement, aggregate, steel, etc. The other part comes from the power consumed in the manufacturing process of components, energy sources such as diesel, such as formwork assembly, concrete mixing, handling and steam curing. Material production carbon emissions and energy consumption can be expressed as follows:

$$\boldsymbol{S_{MAT} = \sum_{i=1}^{n} m_i \cdot EF_i} \tag{5.2}$$

where, i represents the number of types of building materials, m_i (t or m^3) represents the number of building materials used, and EF_i represents the carbon emissions or energy consumption of the building materials of the production unit. The original unit of materials and energy comes from Japan's industrial customs clearance table and related literature. It should be noted that the selection of the appropriate original unit should consider the time background and economic background. Table 1. gives the original unit of related materials[8–13].

Table 5.1. The unit of the case.

Materials	**Emission factor**	**Energy intensities**
Reinforcing bar	0.9 kg CO_2/kg	23.62 MJ/kg
Low-density polyethylene (LDPE)	14.66 kg CO_2/kg	72.24 MJ/kg
Cement	0.3 kg CO_2/kg	3.42 MJ/kg
Aggregate	0.1 kg CO_2/kg	0.56 MJ/kg
Polystyrene board (EPS)	1.94 kg CO_2/kg	75.48 MJ/kg
Timber formwork	5.75 kg CO_2/kg	19.93 MJ/kg
polyurethane foam	2.1 kg CO_2/kg	113.4 MJ/kg
Processing	**Emission factor**	**Energy intensities**
Concrete manufacturing	17.5 kg CO_2/m^3	113.4 MJ/m^3
Prefabricated component production	80.46 CO_2/m^3	1302.47 MJ/m^3
Transporting	73.5 MJ/10^3Yen	4.99 kg/10^3Yen
Dismantling concrete		
Cutting steel bar		
Machine	**Emission factor**	**Energy intensities**
Concrete pump truck	71.5 kg CO_2/kg	957 MJ/h
Concrete mixter	51 kg CO_2/kg	683 MJ/h
Crane	6.31kg/m^3	74.05 MJ/m^3
Power consumption in-situ	4.65 kg CO_2/m^2	61.73 MJ/m^2

5.2.3. On-site work

The energy consumption of carbon emissions during construction is mainly caused by the consumption of fuel and electricity by machinery. According to relevant literature, carbon emissions and energy consumption during construction can be expressed by the following equation:

$$\boldsymbol{T_i = \sum_{i=1}^{n} M_i / E_i} \tag{5.3}$$

$$\boldsymbol{S_{PRO} = \sum_{i=1}^{n} T_i \cdot EE_i \cdot EF_{mac,i}} \tag{5.4}$$

where, i represents the type of machinery, T_i represents the total working time of machinery i, EE_i represents the energy consumption per unit working time of machinery i, $EF_{mac,i}$ represents the carbon emission factor and energy consumption of energy used by machinery i The original unit, M_i

is the total amount of materials using i kinds of machinery, E_i is the working efficiency of the machinery in i. The mechanical efficiency comes from the relevant Japanese standards.

5.2.4. Demolition and collection

The disassembly and waste recovery phase are mainly composed of two parts, S_1: fuel and electricity consumed by machinery during waste collection and disassembly. S_2: Produced by fuel consumed during waste transportation. Carbon emissions or energy consumption can be calculated according to the following equation:

$$\boldsymbol{S_{PRO} = S_1 + S_2} \tag{5.5}$$

$$\boldsymbol{S_1 = \sum_{i=1}^{n} M_k \cdot EF_{mac,k}} \tag{5.6}$$

$$\boldsymbol{S_2 = \sum_{i=1}^{n} D_k \cdot EF_{trans}} \tag{5.7}$$

where, k represents the type of waste; M_k is the total amount of waste used in k types; $EF_{mac,k}$ represents the carbon emission factor or the original unit of energy consumption for processing waste k; D_k（km） represents the distance that building materials k transported from the site to the recycling company; EF_{trans} represents the carbon emissions or energy consumption of the building unit carrying unit. Table 1 gives the carbon emission factors or energy consumption units of different treatment methods [8–13].

5.3. Simulation result and discussion

In this study, the energy consumption and carbon emissions of the two buildings were compared and evaluated based on the scope and data defined above. The results were used to compare the differences between the thermal insulation system of fabricated concrete buildings and cast-in-place concrete buildings. The energy consumption and carbon emission characteristics of the two buildings at different stages of the life cycle were evaluated in detail.

5.3.1.Material consumption

In order to facilitate comparison, the total consumption of building materials is converted into resource unit demand (kg/m^2). Figure 5.4 shows the input resources of the prefabricated concrete building insulation system and the cast-in-place concrete building. The material consumption of the thermal insulation system of prefabricated concrete buildings is 21.11% lower than that of cast-in-place concrete buildings. The material consumption of the wall part is reduced by 21.15%, and the roof part is reduced by 20.98% （Figure 5.5 and Figure 5.6）. The main reason for the material saving of the insulation system of prefabricated concrete buildings is that the prefabricated components use reusable steel formwork in the prefabrication process. The use of wooden formwork in the construction of cast-in-place components avoids the waste of wood. In addition, the prefabricated components are manufactured in the factory to avoid the waste of concrete and steel during construction and improve the quality of the components, thereby reducing the final consumption of both. The assembled components are steam-cured during the curing process, while the cast-in-situ components need to be covered with health materials during the curing process, which increases the amount of materials.

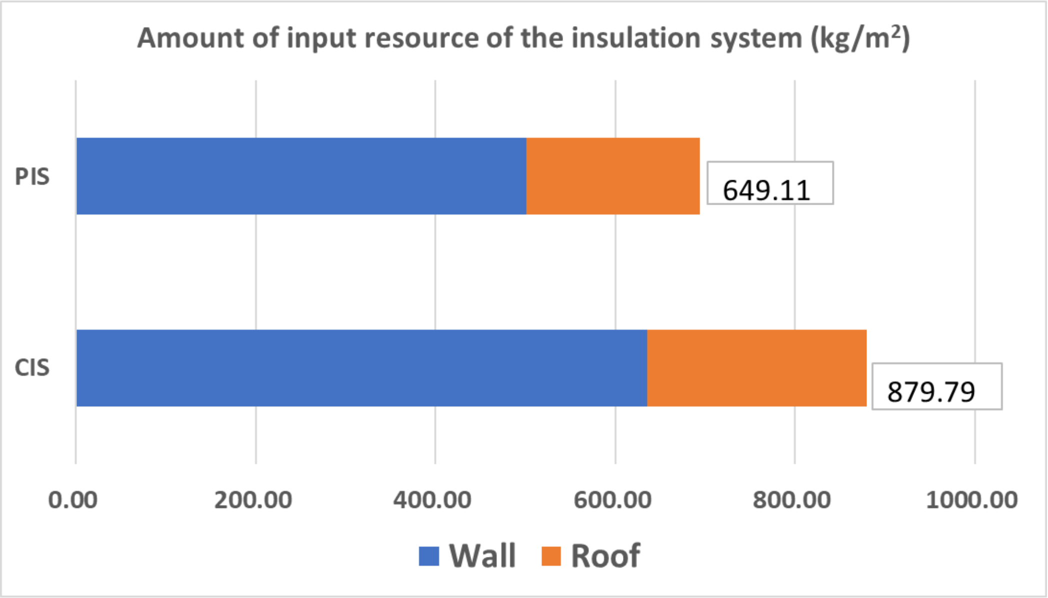

Figure 5.4. Comparison of input resource between PIS and CIS.

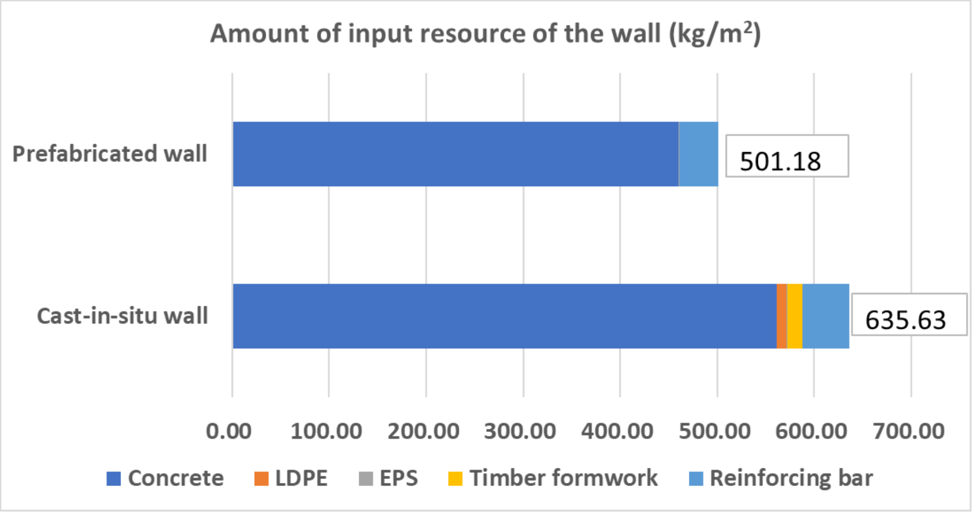

Figure 5.5. Comparison of input resource between prefabricated wall and Cast-in-situ wall.

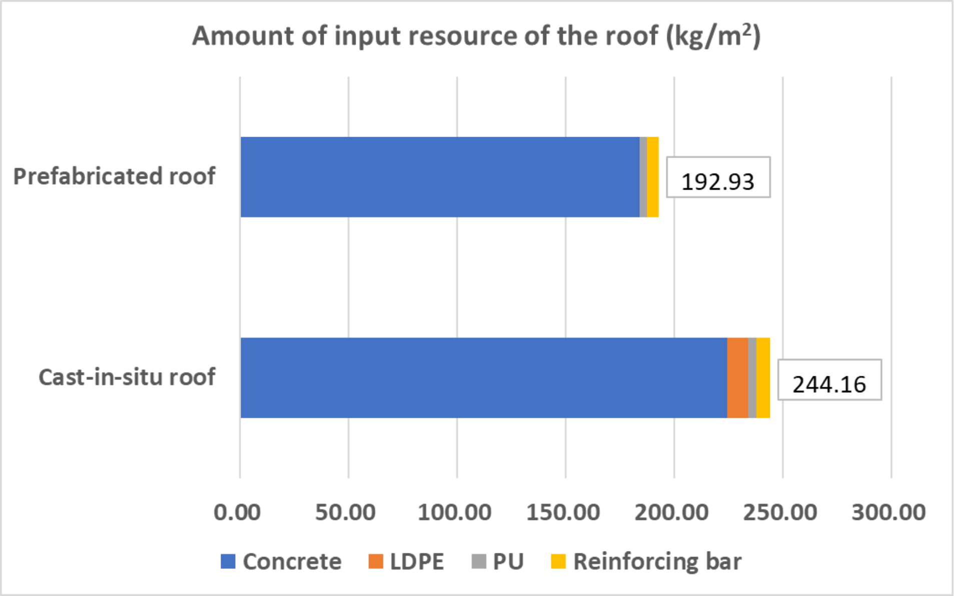

Figure 5.6. Comparison of input resource between prefabricated roof and Cast-in-situ roof.

5.3.2. Comparison of energy consumption of insulation systems during the life cycle

The life cycle energy consumption of the two insulation systems is shown in Figure 5.7. The energy consumption of the walls and roof of PIS is lower than that of CIS. Compared with CIS, the total energy consumption of PIS is reduced by 48.07%. The energy consumption of each stage in the thermal insulation system is shown in Figure 5.8. It can be seen that the energy consumption in the material production stage is the largest, followed by the disassembly and recycling stage, and the construction stage is the smallest. Compared with CIS, the energy consumption of the PIS system in the material production process is greatly reduced, followed by the disassembly and recovery phase, and the energy consumption in the construction phase is the least.

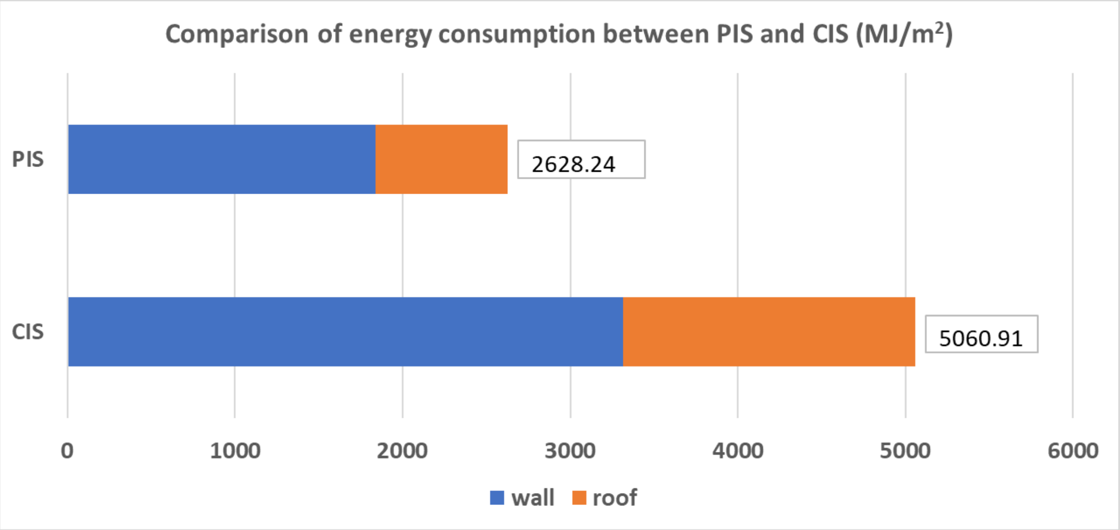

Figure 5.7.Comparison of energy consumption between PIS and CIS.

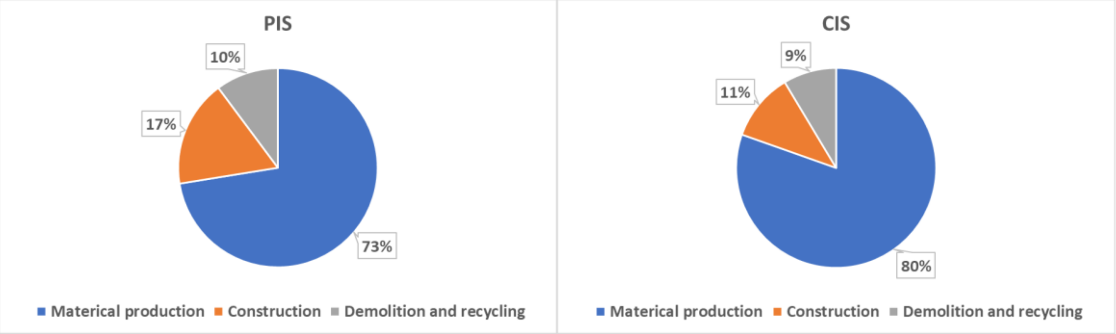

Figure 5.8.Percentage of energy consumption at various stages of the PIS and CIS.

(1). Comparison of energy consumption in the life cycle of wall insulation system

The energy consumption of the two systems in the material production stage is shown in Figure 5.9. In this stage, PIS is reduced by 39.11% compared to CIS. Among them, the energy consumption of LDPE accounts for 25.11% of the energy consumption of the thermal insulation system of cast-in-place concrete buildings, which is a major factor in the high energy consumption of the thermal insulation system of cast-in-place concrete buildings. In addition, wood template energy consumption is also relatively high, accounting for 11.2%. The components of the assembled concrete thermal insulation system are produced in a factory prefabricated manner, using reusable steel formwork, which avoids the use of wood formwork during construction and reduces energy consumption. At the same time, the factory prefabricated method effectively improves the quality of components and reduces the loss of concrete, steel bars and other materials during construction. Compared with the cast-in-place concrete building insulation system, less material consumption also means less energy consumption. In addition, the thermal insulation system of cast-in-place concrete buildings requires the use of LDPE for the maintenance of components during the concrete curing stage, and the additional materials also increase the corresponding energy consumption. This is also a factor that the energy consumption of the thermal insulation system of cast-in-place concrete buildings is higher than that of prefabricated concrete buildings.

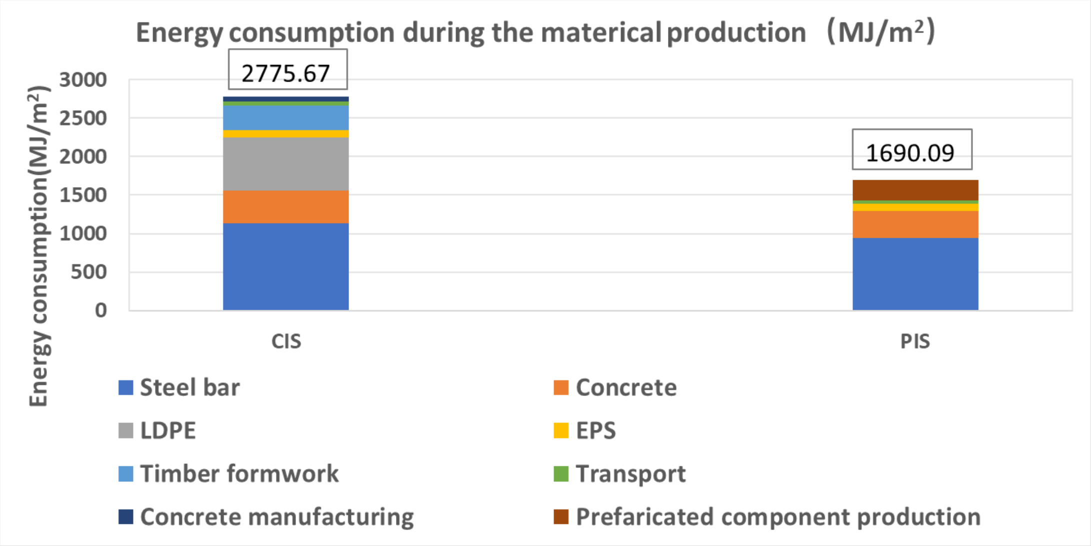

Figure 5.9.Comparison of energy consumption between the CIS and PIS during the material production of the wall.

The energy consumption of the two systems during the construction phase is shown in Figure 5.10. The energy consumption per square meter of PIS is reduced by 190.89 MJ/m^2 compared with CIS, which is 73.52%. Energy consumption during construction is mainly due to the consumption of electricity and fuel by machinery. Concrete mixing energy consumption accounts for 25.22%. The analysis of some actual case data proves that the on-site construction energy consumption of the prefabricated construction method is lower than that of the cast-in-place construction method. Most of the components in the prefabricated building insulation system are prefabricated in the factory, with a high completion rate. In the construction process, it can effectively improve the use efficiency of the construction site, thereby reducing the consumption o49.52f power and fuel on the site and reducing energy consumption. Specifically, in the construction process of prefabricated buildings, the hoisting equipment is used to hoist complete prefabricated components, and the effective utilization rate of the equipment is high. In the construction of traditional buildings, hoisting equipment is often used to lift a single building material, such as steel bars or formwork. The effective use efficiency of the equipment is lower than the prefabricated construction method. In addition, the material use efficiency of the cast-in-place construction method is lower than that of the prefabricated construction method, which results in the material consumption of the cast-in-place concrete building insulation system being higher than the latter, and the increased material consumption also brings additional energy consumption for site construction.

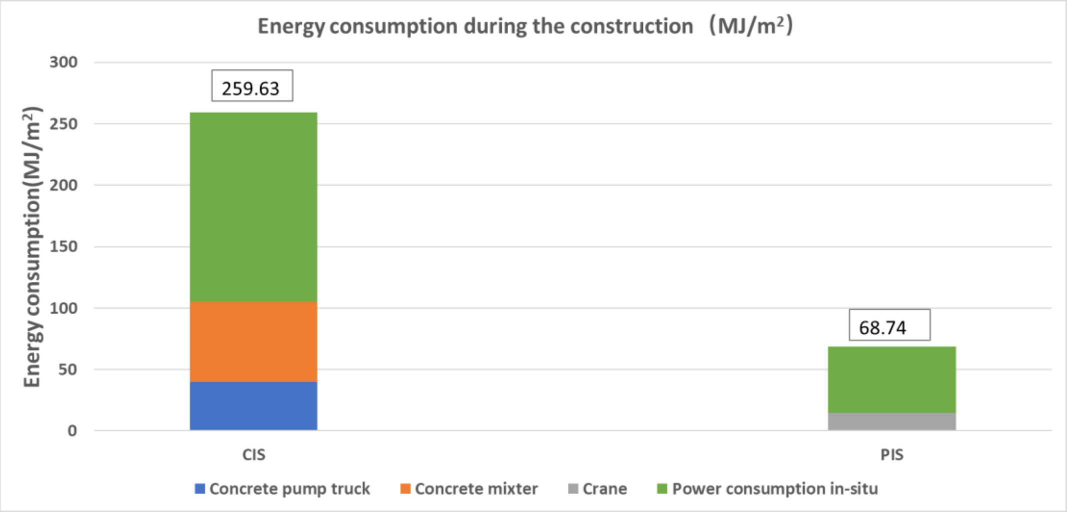

Figure 5.10.Energy consumption between the CIS and PIS during the construction of the wall.

Figure 5.11 shows the energy consumption of the two systems in the demolition and recycling phase. The energy consumption of CIS is 334.59MJ/m^2, the energy consumption of PIS is 168.90MJ/m^2, and PIS is 49.52% lower than CIS. The energy consumption of the prefabricated building and the cast-in-situ building insulation system during the disassembly stage is the same. The difference between the two lies in the recycling stage. The recycling stage is divided into two parts, the recycling of waste generated during construction and dismantling. Compared with prefabricated concrete buildings, in the construction process, the construction method of the cast-in-place concrete building insulation system requires the input of additional materials, such as wooden formwork and concrete health-care materials. At the same time, the construction error caused by the on-site pouring method also generated more construction waste, such as concrete and steel bars. The collection and transportation of these materials and waste consume more fuel, so that the energy consumption of the thermal insulation system of the cast-in-place concrete building is higher than that of the assembly type. The prefabricated factory is a relatively closed and stable environment, which reduces the impact of external natural environment and human factors on component production and reduces the loss of materials. At the same time, modular production is conducive to stable construction, improves product quality, and reduces waste.

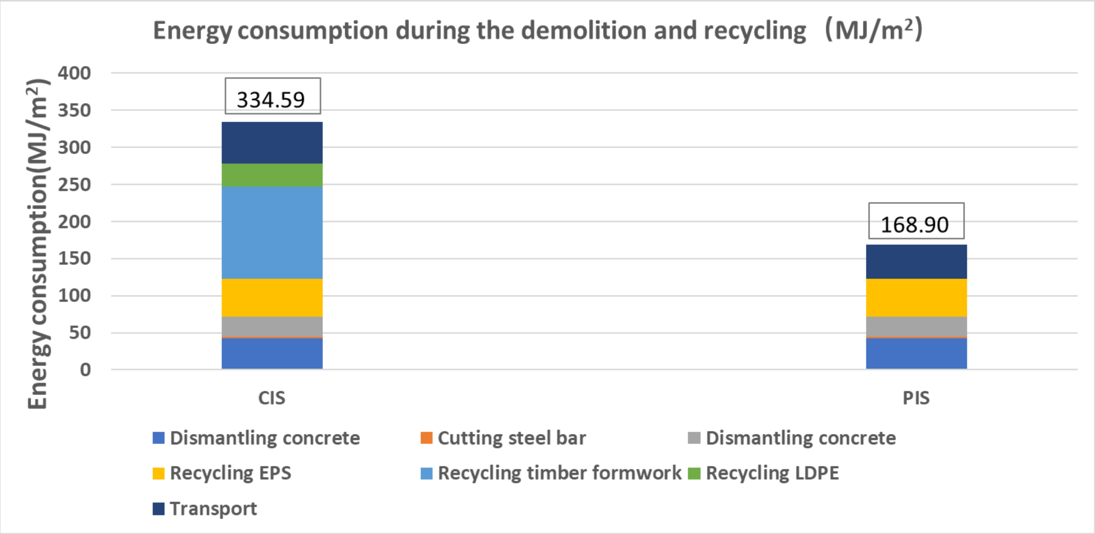

Figure 5.11.Energy consumption between the CIS and PIS during the demolition and recycling of the wall.

(2). Comparison of energy consumption in the life cycle of roof insulation system

The energy consumption of the two systems in the material production stage is shown in Figure 5.12. In this stage, PIS is reduced by 46.5% compared to CIS. The main reason is that on-site construction needs, CIS needs LDPE for concrete maintenance, LDPE energy consumption accounts for 47.81% of CIS energy consumption. On the other hand, the components of the prefabricated concrete insulation system are produced in a factory prefabricated manner, and steam curing is used, which avoids the energy consumption of this part of the material.

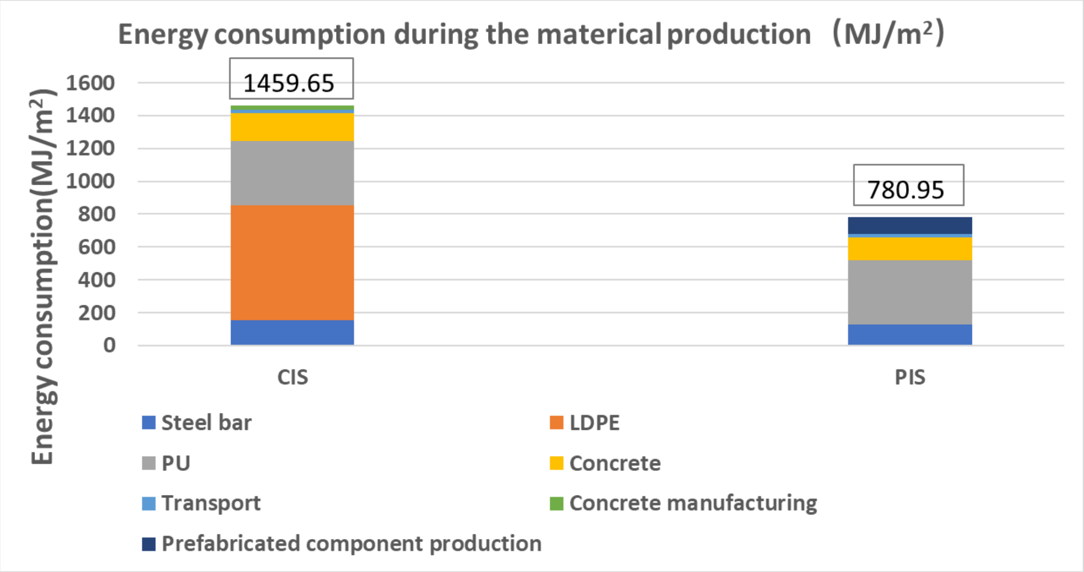

Figure 5.12.Energy consumption between the CIS and PIS during the material production of the

roof.

Figure 5.13 shows the energy consumption of the two systems during the construction phase. The energy consumption per square meter of PIS is reduced by 76.32MJ/m^2 compared with CIS. The lower energy consumption of PIS during construction is mainly due to less construction work on site and efficient lifting methods. At the same time, the reduction of on-site construction materials also reduces the energy consumption during material lifting.

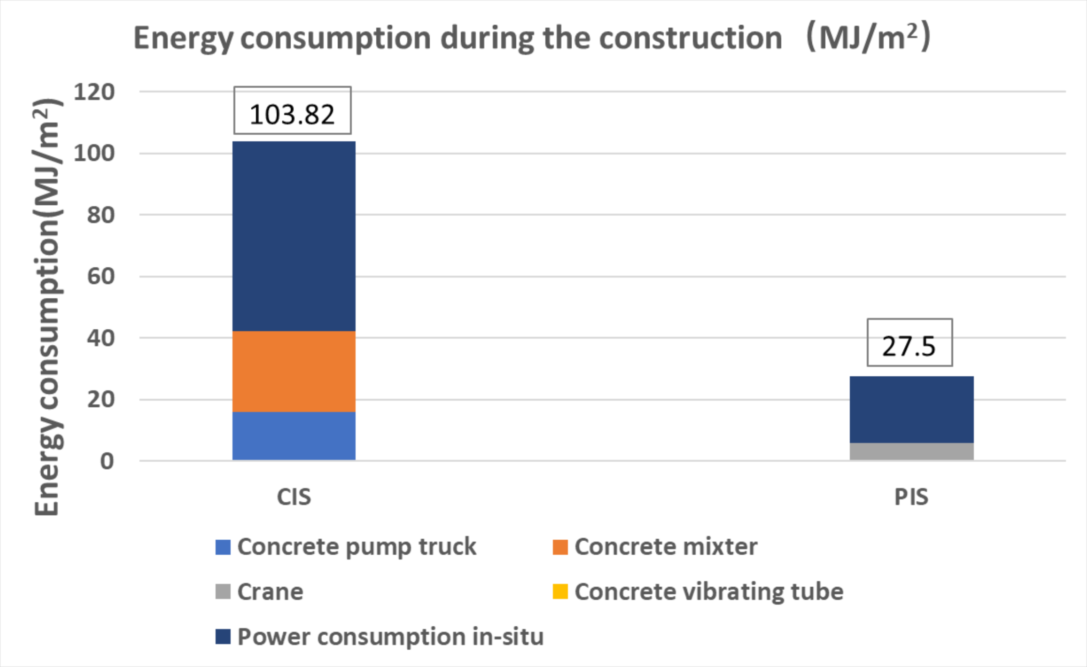

Figure 5.13.Comparison of energy consumption between the CIS and PIS during the construction of the roof.

In the dismantling and recycling stage, the energy consumption of CIS is 178.8MJ/m^2, and the energy consumption of PIS is 162.87MJ/m^2, which is 8.9% lower than that of CIS. At this stage, the energy consumption of the two is similar. The energy consumption of the two in the disassembly stage is the same, the difference is only in the recovery stage. Compared with CIS, PIS avoids the use of some materials in the recycling stage, thereby reducing energy consumption in this stage.

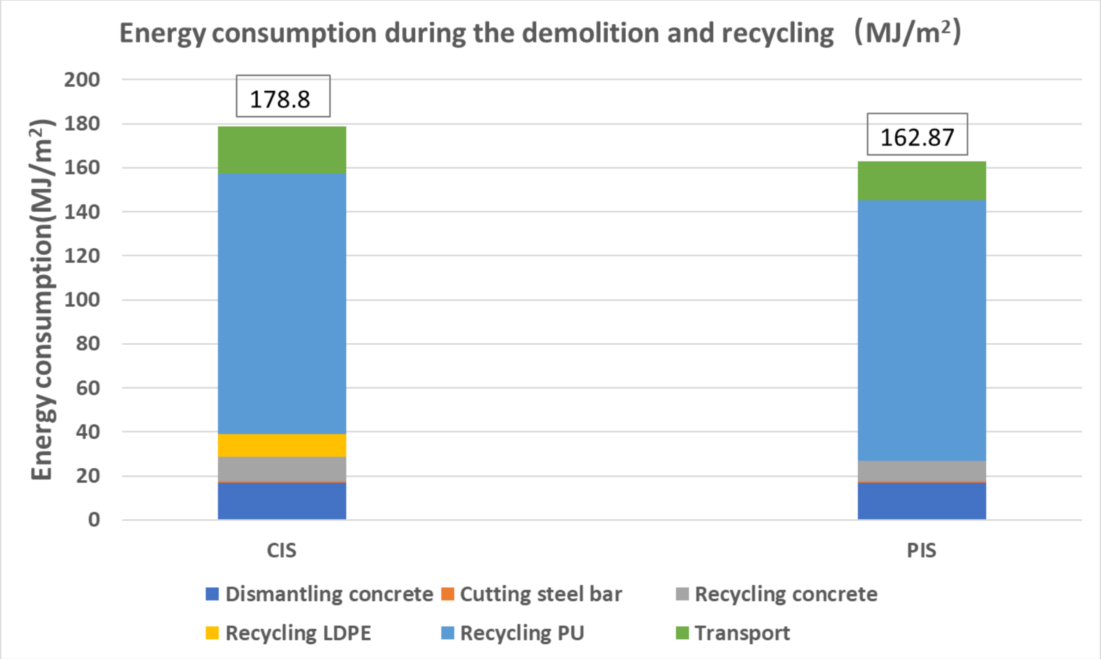

Figure 5.14.Comparison of energy consumption between the CIS and PIS during the construction of the roof.

5.3.3.Comparison of life cycle carbon emissions of insulation systems during the life cycle

The life cycle energy consumption of the two insulation systems is shown in Figure 5.15. The carbon emissions of walls and roofs in PIS are lower than those of CIS. Compared with CIS, the total carbon emissions of PIS are 53.75% lower. Figure 5.16 shows the carbon emissions at each stage of the two insulation systems. The proportion of materials is the largest, and the construction stage is the smallest. Compared with CIS, PIS occupies a relatively low share in the material production process, which shows that PIS can effectively reduce carbon emissions in material production. The overall distribution of carbon emissions of the two systems is similar to energy consumption.

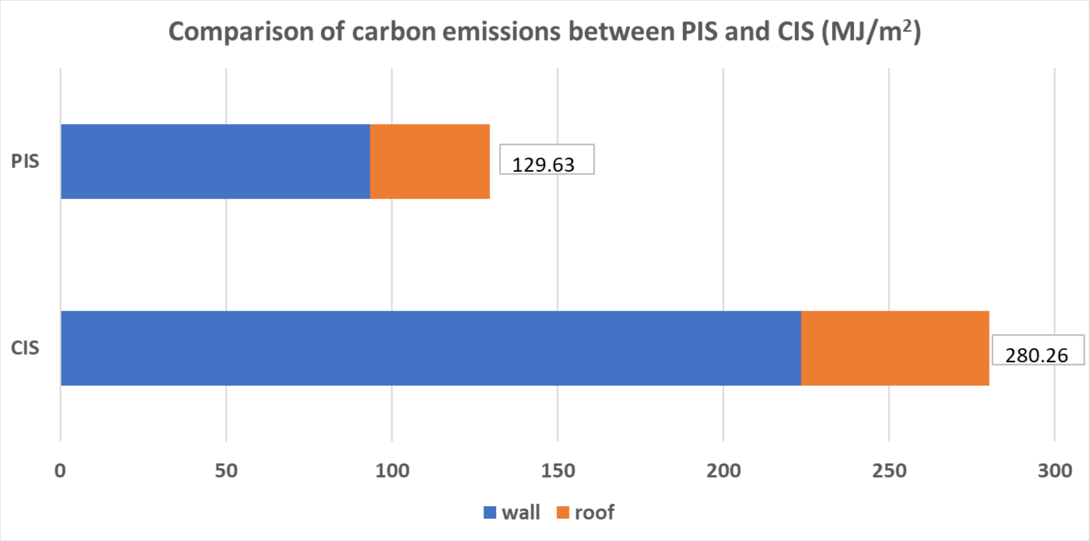

Figure 5.15.Comparison of carbon emissions between PIS and CIS.

Figure 5.16.Percentage of carbon emissions at various stages of the PIS and CIS.

(1). Comparison of carbon emission in the life cycle of wall insulation system

Figure 5.17 shows the carbon emissions of the two systems in the material production stage. In this stage, the reduction of PIS life cycle carbon emissions are mainly due to the reduction of material types and consumption. The increased carbon emissions from the use of wooden formwork accounted for 48.7% of the total carbon emissions in the life cycle of the thermal insulation system of cast-in-place concrete buildings. Therefore, in the construction process, the use of concrete formwork is one of the important factors to increase the carbon emission in CIS life cycle. Even the use of reusable steel or plastic formwork will not be better, because the transportation and construction of these formwork will produce carbon emissions. The prefabricated components are produced in the factory, and there is no energy consumption caused by the formwork lifting and transportation.

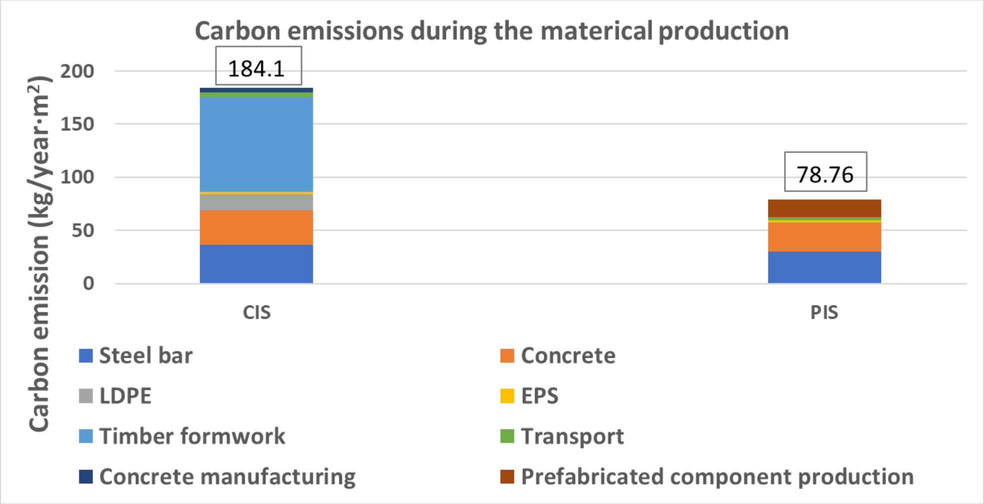

Figure 5.17.Comparison of carbon emissions between the CIS and PIS during the material production of the wall.

The carbon emissions of the two systems during the construction phase are shown in Figure 5.18. The carbon emissions of PIS are 15.26 kg/m^2 lower than that of CIS, which is 72.08%. the prefabricated construction method can effectively improve the effective use of site hoisting machinery. At the same time, the reduced material consumption also avoids the hoisting of related materials. Reduced the use of fuel and electricity for on-site construction machinery and achieved the goal of reducing carbon emissions. There are many on-site procedures in the cast-in-place method, which increases the complexity of construction. The increase in personnel also increases the error rate of construction, thereby increasing the amount of related machinery and materials, which is also the reason for the high carbon emissions of construction on site.

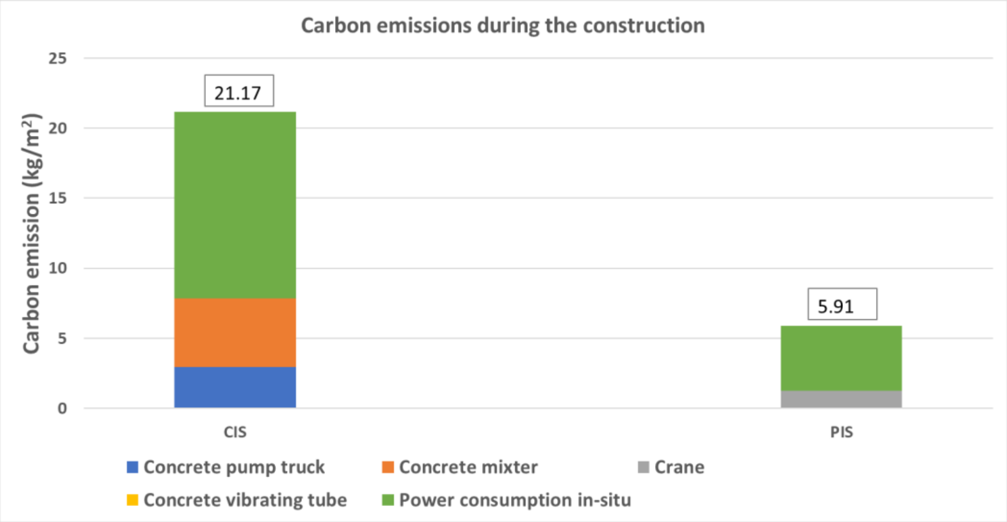

Figure 5.18.Comparison of carbon emissions between the CIS and PIS during the construction of the wall.

Figure 5.19 shows the energy consumption of the two systems in the dismantling and recovery phase. The carbon emissions of PIS are 51.32% lower than those of CIS. The difference between the two systems lies in the recovery phase. Compared with PIS, CIS requires additional materials in the construction process, such as wooden formwork and concrete curing materials. At the same time, the construction error caused by the on-site pouring method also generated more construction waste, such as concrete and steel bars. This also leads to more energy consumption in the waste recycling stage, which in turn generates more carbon emissions.

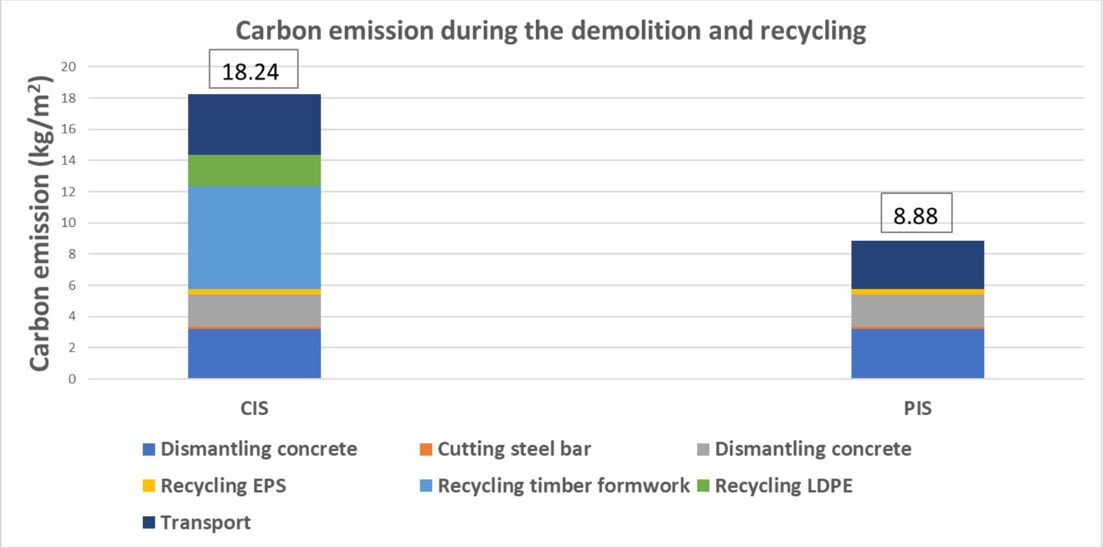

Figure 5.19.Comparison of carbon emissions between the CIS and PIS during the demolition and recycling of the wall.

(2). Comparison of carbon emission in the life cycle of roof insulation system

The carbon emissions of the two systems during the material production stage are shown in Figure 5.20. In this stage, PIS is reduced by 31.11% compared to CIS. The roof reduces the investment in formwork during construction and avoids carbon emissions from this part of the material. The difference between the two is mainly due to the carbon emissions of LDPE. The main reason is the need for on-site construction, CIS needs additional LDPE for concrete maintenance. The carbon emissions of LDPE account for 33.89% of the total, resulting in higher carbon emissions.

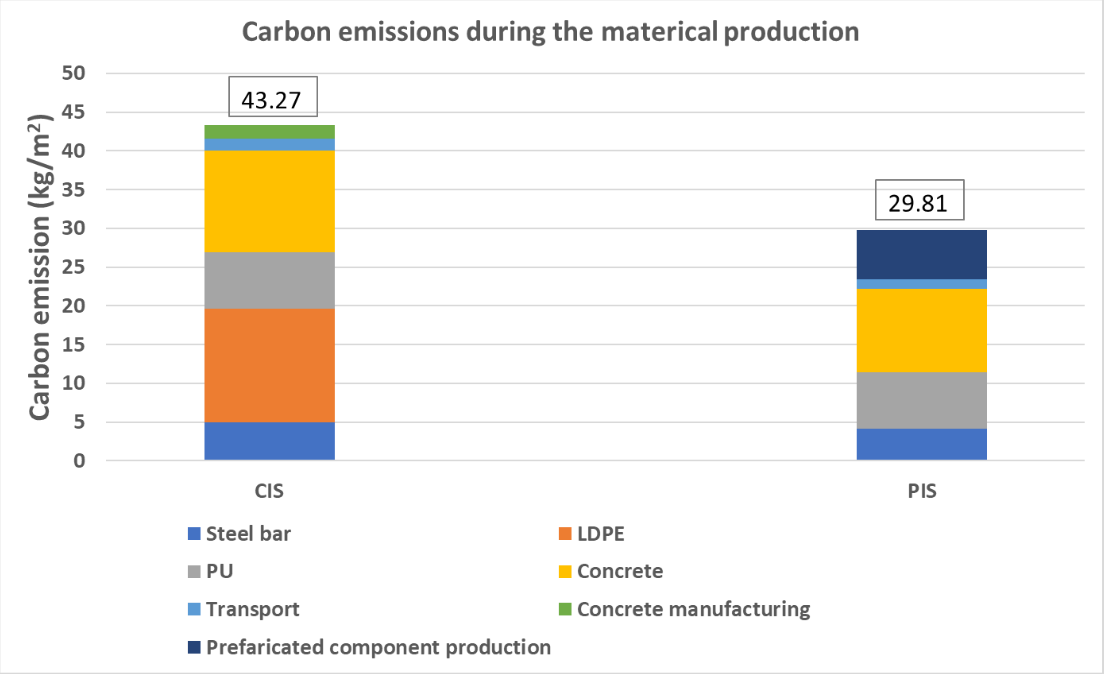

Figure 5.20.Comparison of carbon emissions between the CIS and PIS during the material production of the roof.

The carbon emissions of the two systems during the construction stage are shown in Figure 5.21. Compared with the material production stage, the carbon emissions in this stage are smaller. PIS is lower than CIS by 71.9%, the difference between the two mainly comes from the lifting process. Although the carbon emissions of the fabricated components are higher during the production process, the carbon emissions from the on-site construction are low, thereby reducing the overall carbon emissions throughout the construction phase.

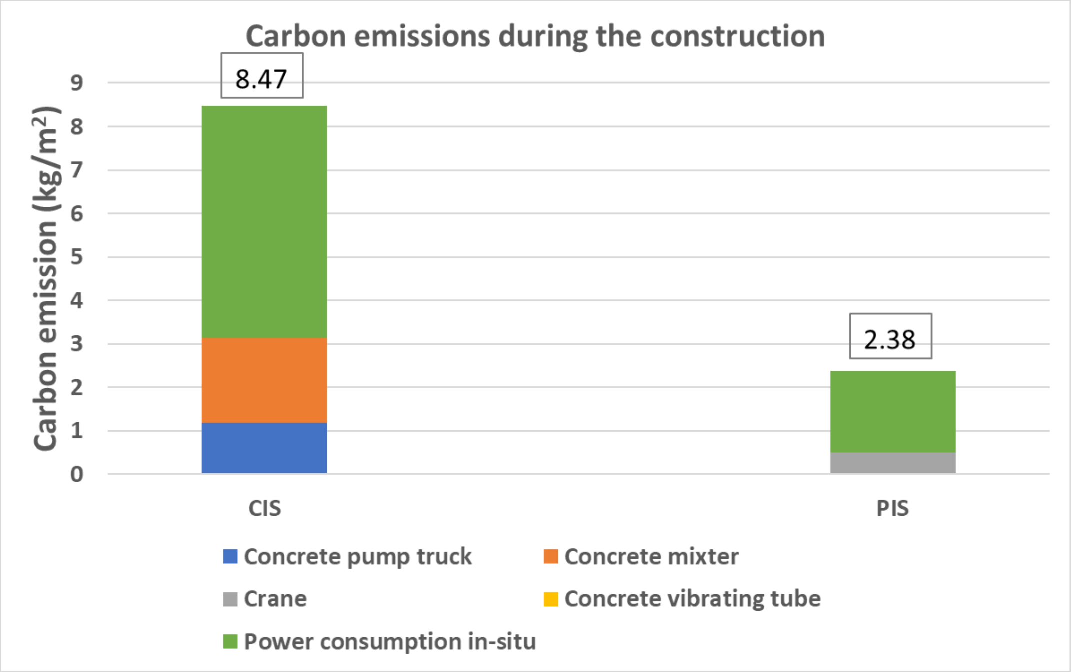

Figure 5.21.Comparison of carbon emissions between the CIS and PIS during the construction of the roof.

Compared with the other two stages, the carbon emissions during the on-site recovery and disassembly stage are lower. The carbon emissions of the two systems at this stage are shown in Figure 5.22. The carbon emission of PIS is lower than that of CIS, which is reduced by 21.84%. The reduction in PIS carbon emissions is due to the reduction in the amount of materials used, mainly because the factory-made production method avoids the use of LDPE and wooden formwork. At the same time, the construction quality of the factory also reduces the waste of materials, thus reducing carbon emissions.

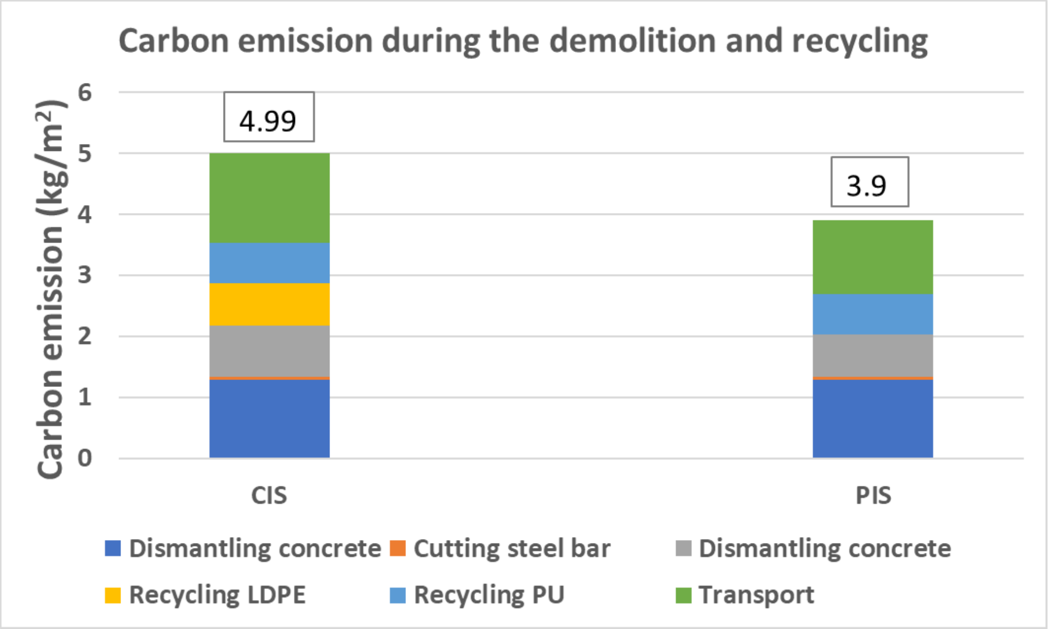

Figure 5.22.Comparison of carbon emissions between the CIS and PIS during the demolition and recycling of the roof.

5.3.4. Comparison of life cycle cost of insulation systems during the life cycle

During the material production stage, the cost of the two systems at this stage are shown in Figure 5.23 and Figure 5.24. The cost of prefabricated wall is lower than the cost of cast-in-situ wall, which is reduced 9.8%. It is due to the reduction in the amount of materials used. The cost of prefabricated roofs is higher than the cost of cast-in-situ roofs, which is increased 43.64%. The reason is that the roof avoids the use of wooden formwork, thereby reducing the cost of the material production and transportation stages.

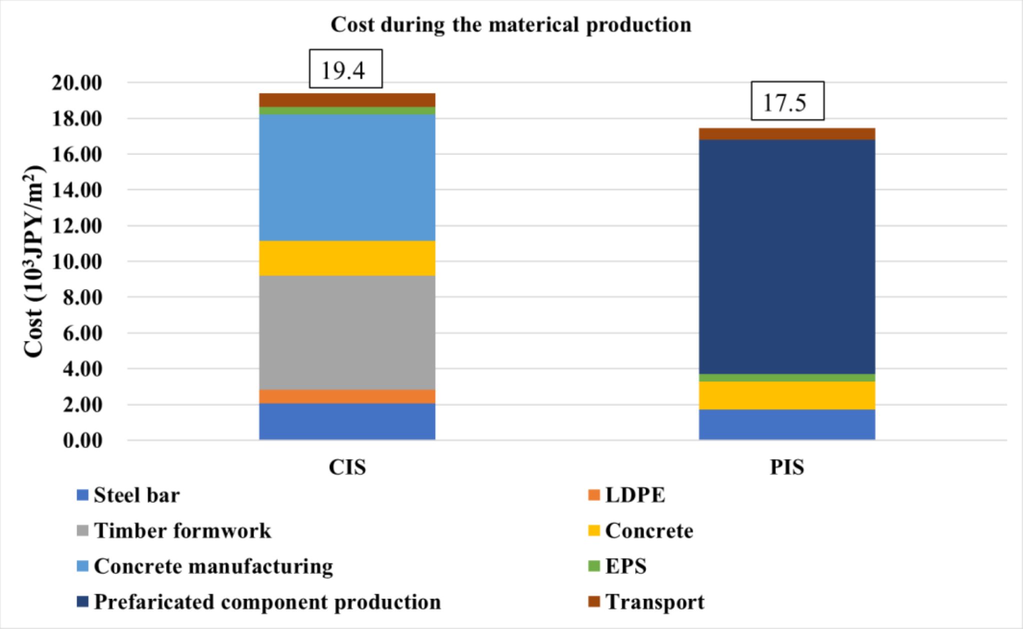

Figure 5.23. Cost during the material production of the wall（10^3JPY/m^2）.

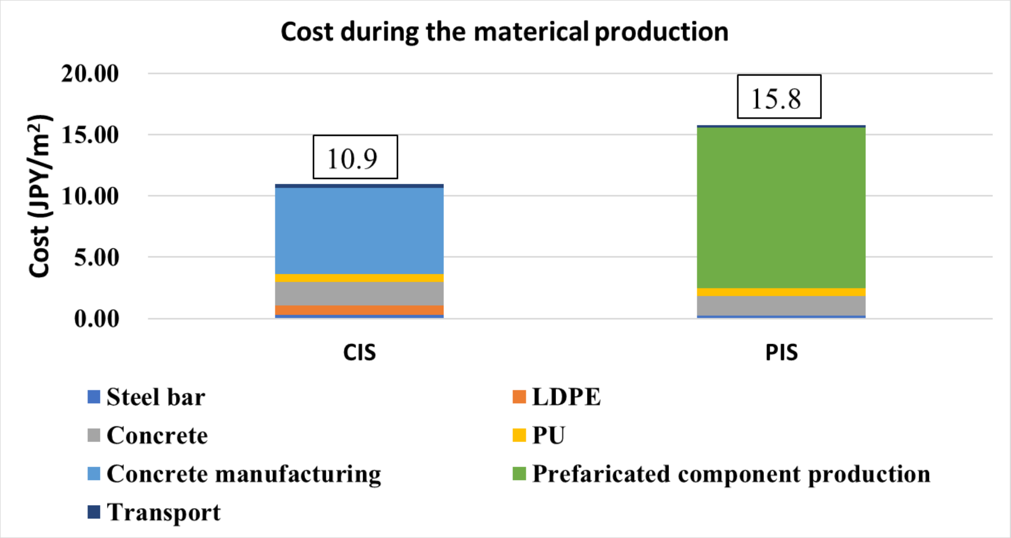

Figure 5.24. Cost during the material production of the roof（10^3JPY/m^2）.

During the construction stage, the cost of the two systems at this stage are shown in Figure 5.25 and Figure 5.26. The cost of prefabricated wall is lower than the cost of cast-in-situ wall, which is reduced 47.6%. The cost of prefabricated roofs is lower than the cost of cast-in-situ roofs, which is increased 44.9%. The reason is that PIS doesn't need to pay for concrete mixer and concrete pump truck. And there is lower power consumption in-situ.

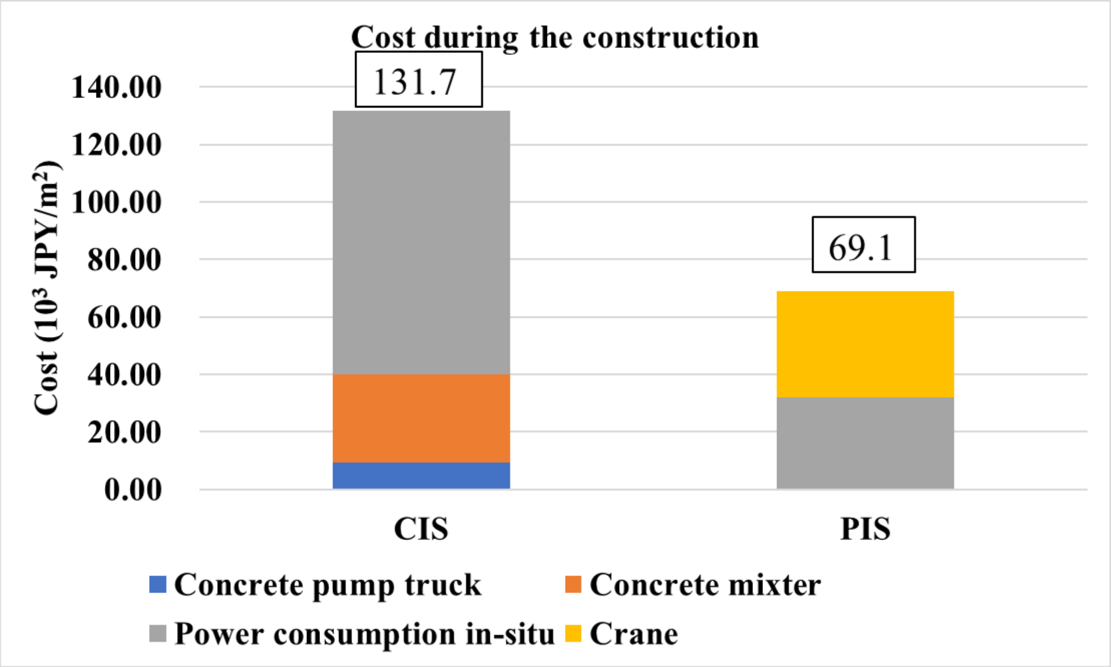

Figure 5.25. Cost during the construction of the wall（JPY/m^2）.

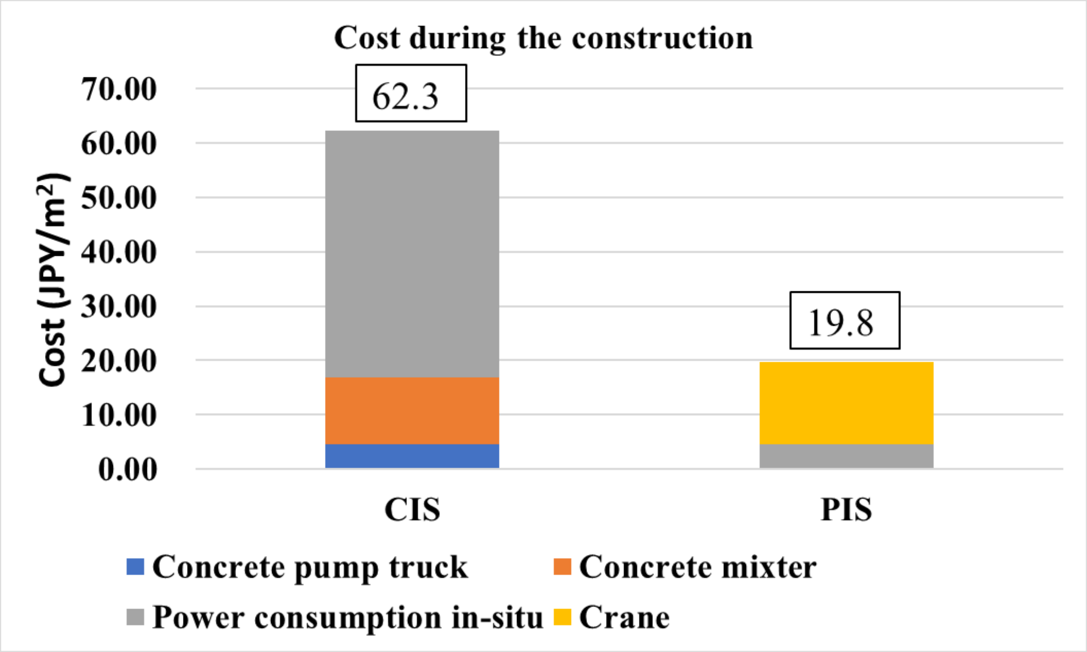

Figure 5.26. Cost during the construction of the roof（JPY/m^2）.

During the demolition and recycling stage，the cost of the two systems at this stage are shown in Figure 5.27 and Figure 5.28. The cost of PIS less than CIS because there are less materials need to be recycled. Compared with CIS, the wall and roof of PIS are reduced by 16.1% and 11.6%.

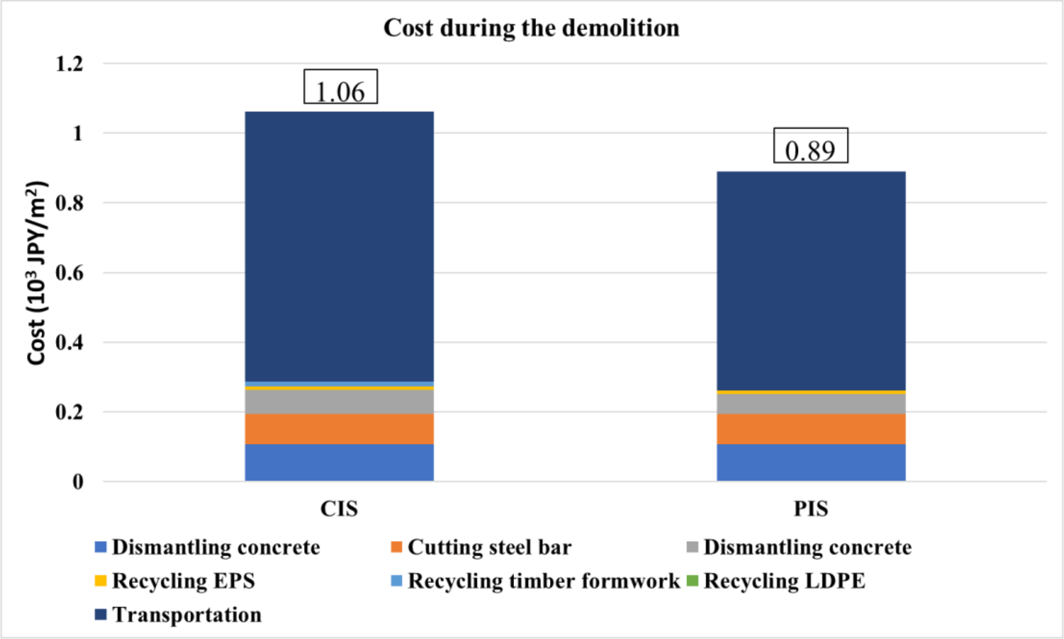

Figure 5.27. Cost during demolition and recycling of the wall（10^3 JPY/m^2）.

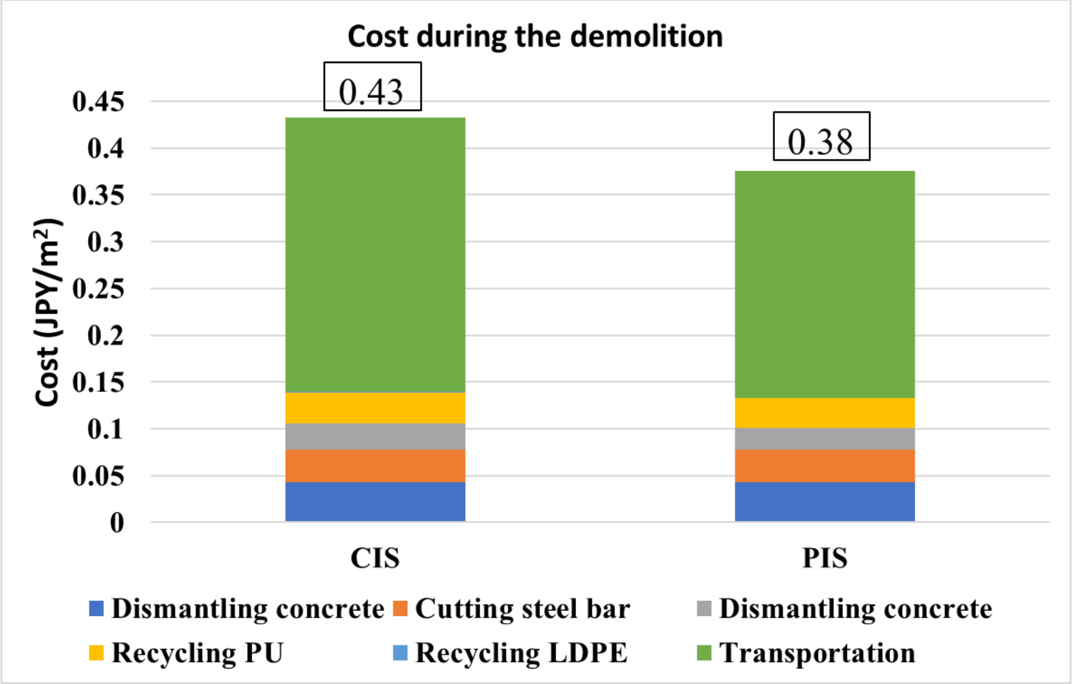

Figure 5.28. Cost during demolition and recycling of the roof（ 10^3 JPY/m^2）.

5.4. Summaries

In this study, the life cycle models of prefabricated and cast-in-place concrete insulation systems are constructed. Based on this model, the energy consumption and carbon emissions of each stage of the two life cycles are analyzed. The energy consumption and carbon emissions of the assembled concrete thermal insulation system at all stages of the life cycle are lower than that of cast-in-place concrete buildings, and the total energy consumption is reduced by 48.07%. The energy saving effect is most obvious in the material production stage, which is reduced by 41.65%. The construction and dismantling recovery stages were reduced by 73.52% and 35.38% respectively. The total carbon emission of the assembled concrete thermal insulation system is 53.75% lower than that of the cast-in-place type. The material production stage reached 52.38%, and the construction and disassembly recovery stages were 72.03% and 45.03% respectively. In terms of material input, the prefabricated concrete insulation system has reduced by 26.22% compared with the cast-in-place thermal insulation system, in which the material consumption of the wall part is reduced by 21.15% and the roof part is reduced by 20.98%. The reason for the above energy saving and carbon emission reduction is that the prefabricated components avoid the use of wooden formwork and concrete curing materials. At the same time, the prefabricated production method of building components in the factory improves the quality of products and reduces the generation of waste during construction. Most of the components in the prefabricated building insulation system are prefabricated in the factory. In the construction process, it can effectively improve the use efficiency of the construction site, thereby reducing the consumption of power and fuel on the site and reducing energy consumption.

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Chapter 6. Regional Applicability Performance of Envelope Insulation system in Prefabricated Buildings

6.1. Introduction

From the analysis in Chapter 3, it can be seen that energy efficiency in building operation is of great significance for reducing the environmental load of the future construction industry. At present, the application and promotion of building energy-saving technologies often only focus on the operation energy consumption or energy-saving technology. However, many energy-saving technologies will increase the investment in early-stage product production, and accordingly increase energy consumption and environmental load. If the choice is not reasonable, it may lead to an increase in the cumulative environmental load of the construction industry over the years. Therefore, the environmental performance of energy-saving technologies must be analyzed and evaluated from the perspective of the entire life cycle. This chapter will use specific energy-saving technology as an example to explain how to evaluate the environmental performance of building energy-saving technology from the perspective of life cycle, so as to provide a theoretical reference for the rational selection of building energy-saving technology. And then from the micro level to ensure the realization of sustainable development of the construction industry. The specific technology is currently one of the main energy-saving measures of the energy-saving structure of the envelope, and it is also the most controversial technology in practical applications. Therefore, this chapter chooses it as the research object, and specifically analyzes the application and significance of the life cycle assessment method in it. Considering the large latitudes in Japan and the different climatic conditions in different regions, this chapter also conducted a regional applicability study on the technology.

Insulation is the main technical measure to increase the thermal characteristics of the non-transparent envelope, and it is also the most energy-saving technical means currently used in buildings. In the building life cycle, the energy consumption in the operation phase is the largest, with the highest energy consumption in cooling and heating. The application of reasonable thermal insulation layer can effectively reduce the energy consumption of the building. Increasing the thickness of the insulation layer is one of the main measures for building energy saving. However, the production and transportation of insulation materials also consume a lot of energy and resources and emit pollutants. Increasing the thickness of the insulation layer will reduce the operating energy consumption and environmental load of the building. On the other hand, it will also increase energy consumption and environmental load at the production stage. From the perspective of the entire life cycle of the building, the increased energy consumption and environmental load generated by the insulation material may offset the reduced energy consumption and environmental load during the building's operating phase. Therefore, it is necessary to analyze the relationship between energy consumption and environmental load. When the same type of building is located in different climate zones, the cooling and heating loads vary greatly. Correspondingly, the thermal design requirements of buildings are also different. Therefore, it is necessary to calculate the energy consumption and environmental load of buildings in different thermal zones, and analyze the relationship between the change in the thickness of the insulation layer in different climate zones and the energy consumption and environmental impact during the operation phase.

In this chapter, based on the research results of Chapter 5, the energy consumption of air conditioners in prefabricated buildings based on external insulation technology is simulated using EnergyPlus software. The relationship between production energy consumption and carbon emissions of thermal insulation materials with different thicknesses and building operation energy consumption and carbon emissions is analyzed. And the above model is extended to different thermal engineering partitions in Japan. Based on the analysis results, suggestions are made for the minimum insulation thickness of different thermal zones.

6.2. Method

The energy consumption and environmental load of thermal insulation materials are composed of the production, construction and removal of thermal insulation materials. The environmental load of insulation removal treatment is similar to the analysis of other building materials products and is included in the insulation production list. The energy consumption and environmental load of the building during the operation phase only consider heating and cooling. The evaluation of different insulation thickness schemes will be analyzed from the aspects of energy consumption and carbon emissions. The total life cycle is calculated according to equation (6.1) and (6.2) [1].

$$\mathrm{LC} = \mathrm{IP} + \mathrm{BO} \tag{6.1}$$

$$\mathrm{R} = \frac{\mathrm{LC}_{n+1}}{\mathrm{LC}_n} \tag{6.2}$$

IP: Energy consumption and environmental load at the production stage of insulation layer
BO: Building annual energy consumption and environmental load
LC: Comprehensive energy consumption or comprehensive environmental load

Different programs have different total energy consumption or total environmental load. When the ratio R of the two is greater than 1, it means that the overall energy consumption of LC_{n+1} is greater than that of scheme LC_n, which means that the energy saving or carbon emission reduction of scheme n is better than that of scheme n + 1.

6.3.Simulation model conditions

The influence of climate on building load characteristics is very significant. When similar buildings are located in different climatic zones, the cooling and heating loads are very different, and the thermal design of the building should also be different. Figure 6.1 shows the Japanese building thermal zones. In this chapter, seven representative cities were selected for research in seven major thermal climate regions in Japan, as shown in Table 6.1. The researched building cases were placed in these seven cities, and the life cycle environmental performance of the building was analyzed and analyzed through simulation calculation [2].

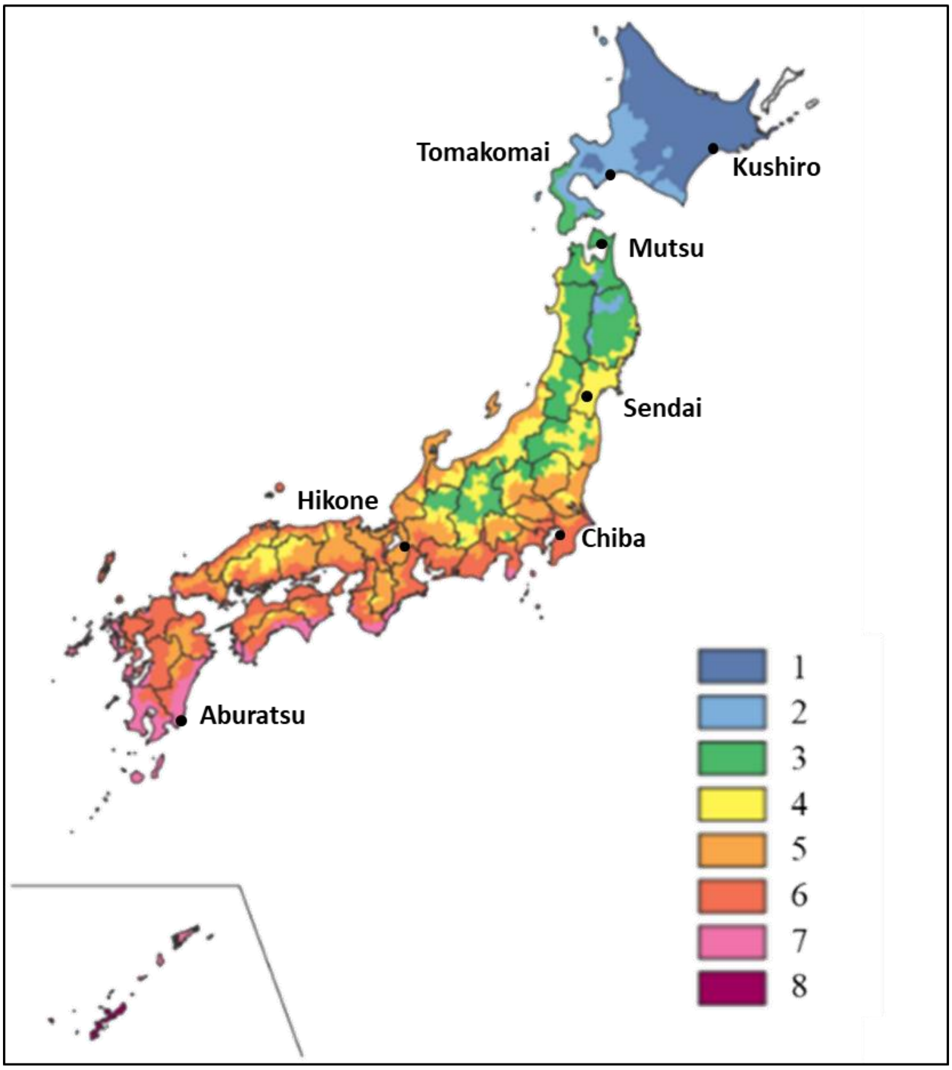

Figure 6.1 Japan climate zone map

Table 6.1. 7 selected cities in Japan

Thermal Climate Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Location	Kushiro	Tomakomai	Mutsu	Sendai	Hikone	Aburatsu	Muroran

6.4. Results and Discussion

In this section, the relationship between building energy efficiency and insulation thickness is first analyzed. Based on the simulation of prefabricated building external insulation partition walls in Chapter 5, the relationship between the carbon emission and energy consumption of the full life cycle prefabricated insulation system and HVAC during the building operation phase is analyzed. And from the perspective of energy consumption and carbon emissions, the thickness of the heat insulation layer suitable for different thermal industrial zones in Japan is calculated.

6.4.1.Energy saving potential of insulation improvement of envelope area

Figure 6.2 shows the relationship between insulation thickness and energy saving. The x-axis represents the gradually increasing thickness of the insulation layer based on the basic design, and the y-axis represents the total energy savings. Different colored lines represent selected case cities in different thermal engineering subdivisions in Japan. It can be seen that as the insulation thickness increases, the heat transfer coefficient of the outer wall roof decreases, and the construction load in various regions continues to decrease, but the rate of decline gradually decreases as the insulation thickness increases. In the first to third thermal engineering zones, the optimization of the insulation layer has a more obvious effect on building energy saving. In the fourth to seventh regions, the optimization of the insulation layer has no obvious effect on building energy saving. This shows that the heat load is more significantly affected by the thickness of the insulation (Kushiro, Tomakamai and Mutsu). As the latitude and R value increase, the amount of energy saving increases dramatically.

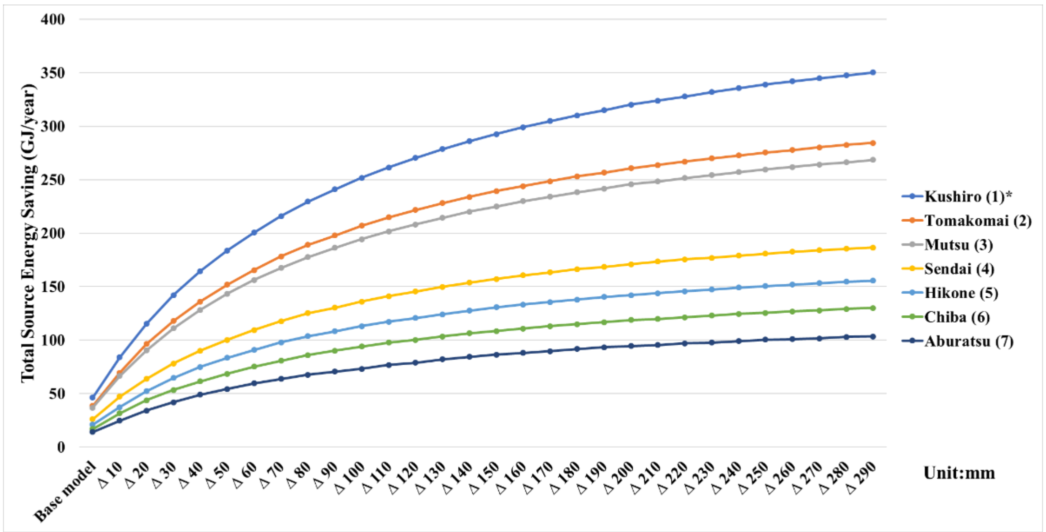

Figure 6.2 Total source energy saving with thermal thickness increase.

* The number represents the thermal climate zone where the city is located

The change law of building heating load is the same as the law of total energy consumption. The heating load decreases with the increase of the thickness of the insulation layer in each thermal engineering zone. The energy saving of heating load in zone 1 to zone 4 is close to the total energy saving (Figure 6.3). The results show that increasing the thickness of the insulation layer has an energy-saving effect on the thermal load of each thermal engineering building. However, in zone 5 to zone 6, the range of change is not obvious, and the effect of building energy saving by improving the performance of the envelope is not ideal. The reason should be that the temperature in these areas is relatively high and the heating load of the building is low. Energy efficiency of the building should be achieved through other design strategies, such as improving natural ventilation and reasonable shading design.

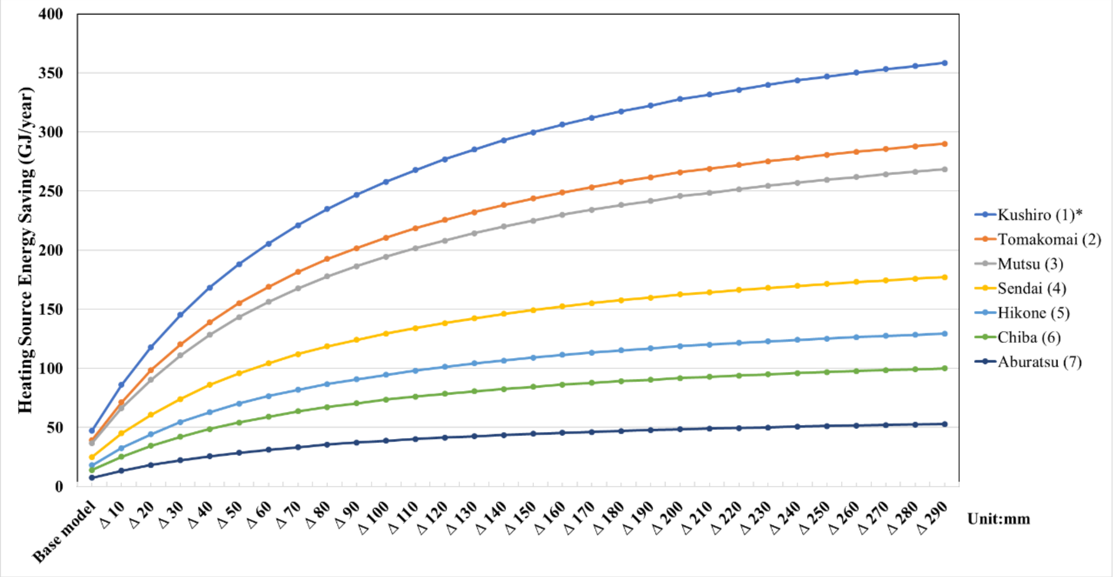

Figure 6.3 Heating source energy saving with thermal thickness increase

Figure 6.4 shows the energy saving effect of building cooling load as the thickness of the insulation layer increases. In zone 3 to zone 7, increasing the thickness of the insulation layer has an energy-saving effect, but the amount is smaller. In zone 1 and zone 2, increasing the thickness of the insulation will increase the energy consumption of the building. This also shows that the improvement of the thermal performance of the building envelope will not significantly affect the cooling energy consumption.

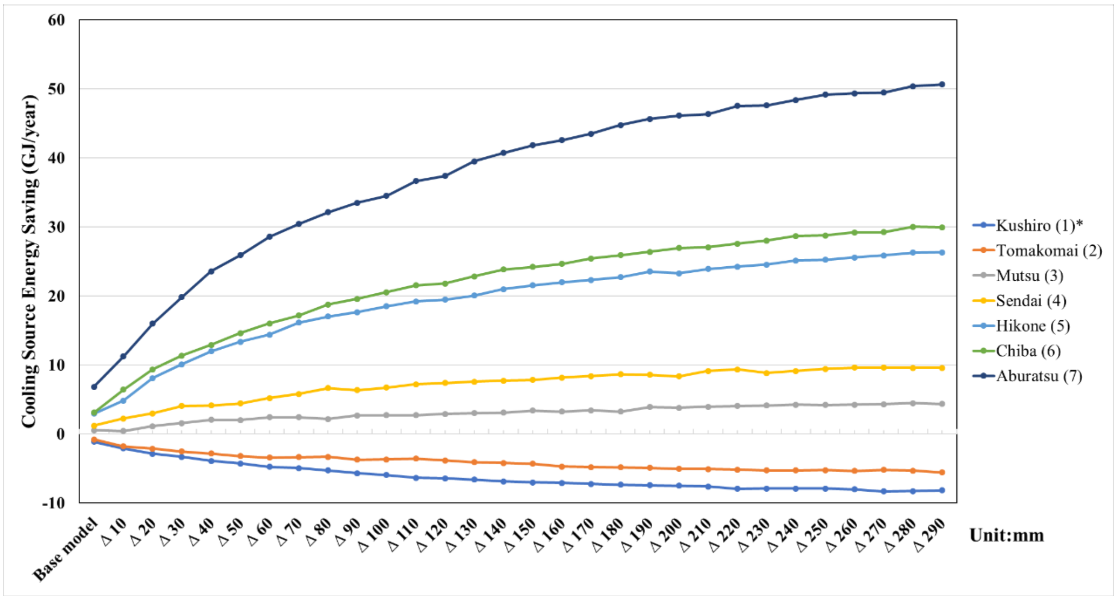

Figure 6.4 Cooling source energy saving with thermal insulation thickness increase

6.4.2. Regional energy consumption performance of envelope insulation system

Figure 6.5 shows the energy consumption of Kushiro in zone 1. The total energy consumption of the insulation system decreases first and then increases as the thickness of the insulation layer increases. When the thickness of the wall and roof insulation layers reaches 220mm and 285mm respectively, the overall energy consumption of the insulation system is the lowest. After the thickness of the insulation layer exceeds this limit, the overall energy consumption of the system gradually increases. This shows that the energy consumption reduced by increasing the thickness of the insulation layer is less than the energy consumption of the material input when increasing the insulation material.

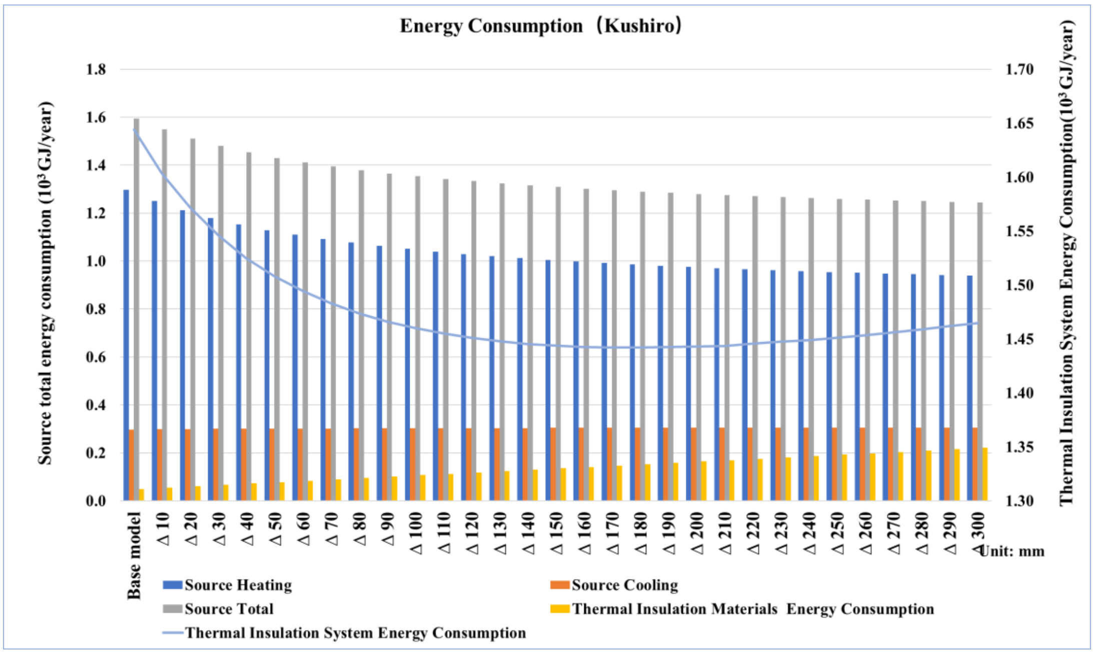

Figure 6.5 Energy consumption of the thermal insulation system in Kushiro.

The energy consumption of Tomakomai in zone 2 is shown in Figure 6.6. The law of the total energy consumption of the thermal insulation system is the same as the case of zone1, which first decreases and then increases. However, the thickness of the insulation layer that has achieved the lowest energy consumption of the system has been reduced. The thickness of the wall and roof insulation layers are 200mm and 265mm respectively. After exceeding this limit, the overall energy consumption of the system gradually increases.

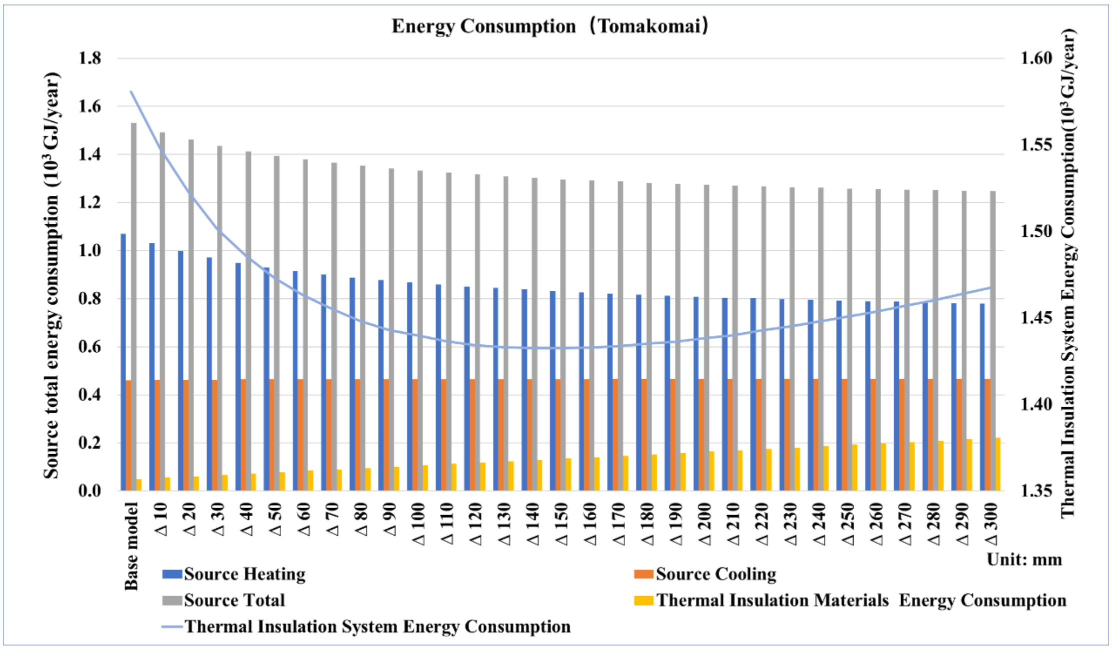

Figure 6.6 Energy consumption of the thermal insulation system in Tomakomai.

Figure 6.7 shows the energy consumption at Mutsu. The total energy consumption of its insulation system first decreases and then increases. The system has the lowest energy consumption when the thickness of the wall and roof insulation layers is 200mm and 265mm, and the overall energy consumption of the system beyond this limit gradually increases. In this study, the optimal insulation thickness of zone 3 and zone 2 is the same, which is similar to the thickness of zone 1. The reason is that the heating load of zone 1 to zone 3 accounts for a relatively large amount and the geographical location is similar, so the thickness of the best insulation layer is relatively close.

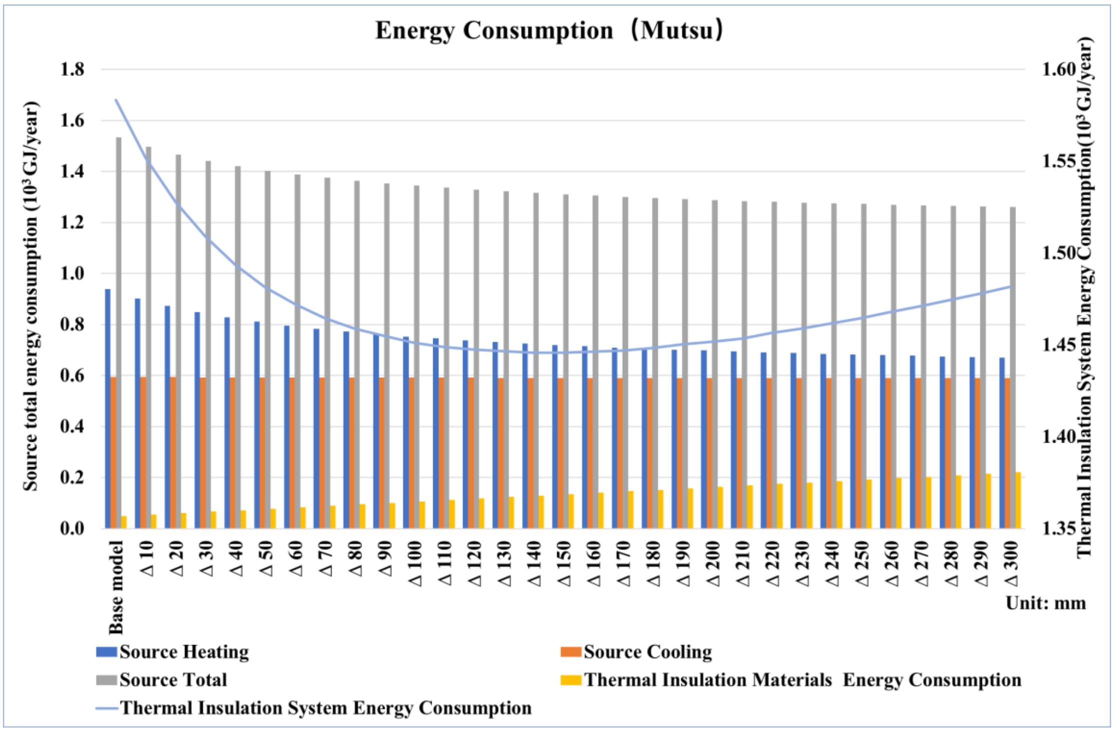

Figure 6.7 Energy consumption of the thermal insulation system in Mutsu.

Figure 6.8 shows the energy consumption of Sendai. The trend of the total energy consumption of the thermal insulation system is the same as the above three zones. The system has the lowest energy consumption when the thickness of the wall and roof insulation layers are 140mm and 205mm, and the overall energy consumption of the system beyond this limit gradually increases. The thickness of the best insulation layer in Zone 4 is much different from the first three zones. The reason is that the area is dominated by cooling load energy consumption, and the effect of increasing the thickness of the insulation layer to achieve energy saving in the insulation system is not obvious.

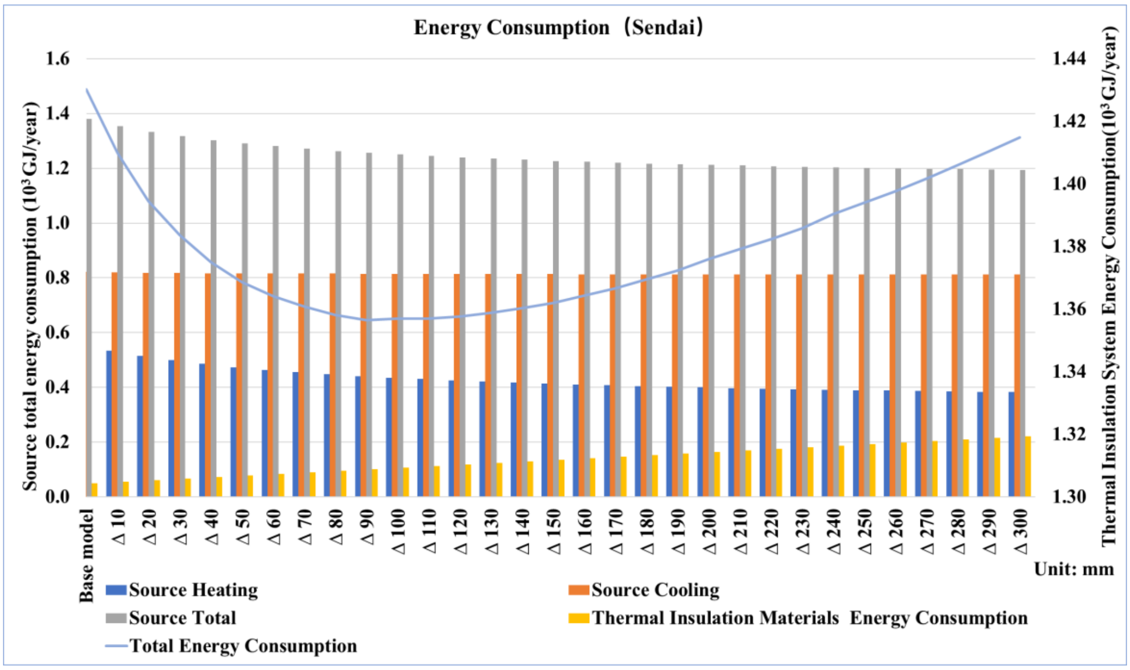

Figure 6.8 Energy consumption of the thermal insulation system in Sendai.

Hikone's energy consumption is shown in Figure 6.9. The system has the lowest energy consumption when the thickness of the wall and roof insulation layers are 130mm and 195mm, and the overall energy consumption of the system beyond this limit gradually increases. As the overall energy consumption of the system gradually increases, the total energy consumption of its thermal insulation system decreases first and then increases. The difference between the optimal thickness of zone 5 and zone 4 is very small, because zone 5 is also dominated by cooling load. This area should achieve energy saving of the insulation system through ventilation or other means.

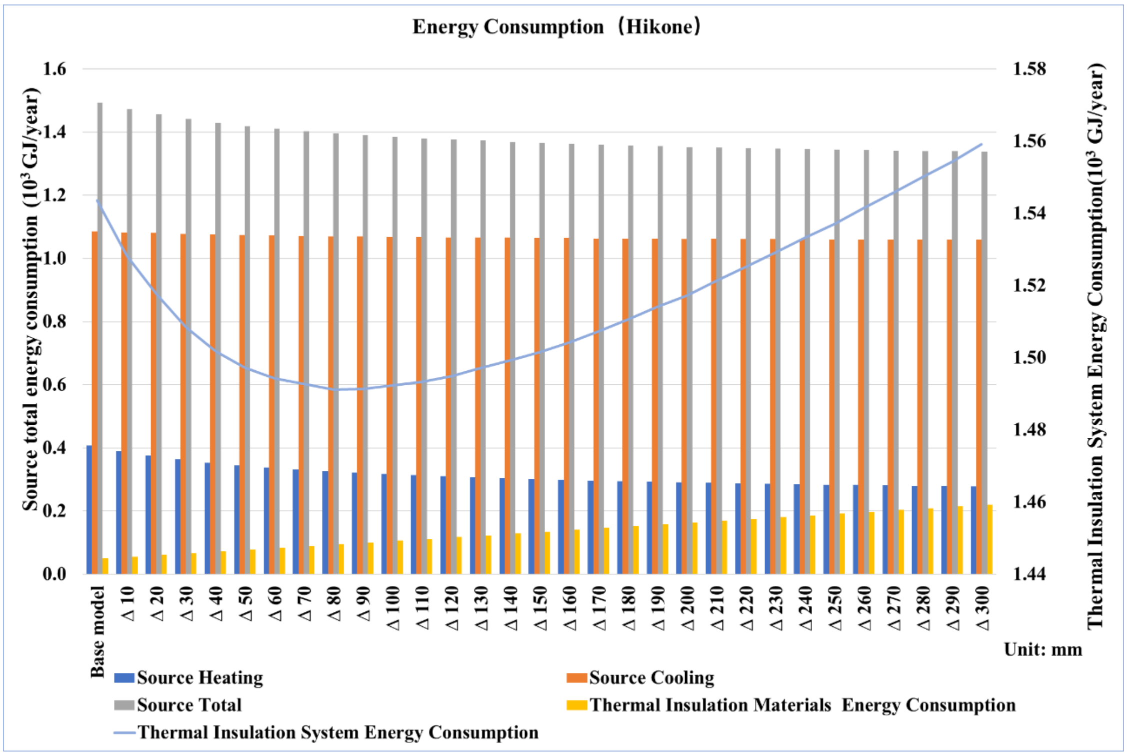

Figure 6.9 Energy consumption of the thermal insulation system in Sendai.

Figure 6.10 shows the energy consumption of Chiba. The total energy consumption of the insulation system is the same as zone 4 and zone 5. The system has the lowest energy consumption when the wall and roof insulation layers are thin, at 120mm and 185mm respectively. The overall energy consumption of the system beyond this limit gradually increases. Compared with the first two zones, the ratio of the building's cooling load to heating load is three times higher, which is the reason why its optimal insulation layer is thinner.

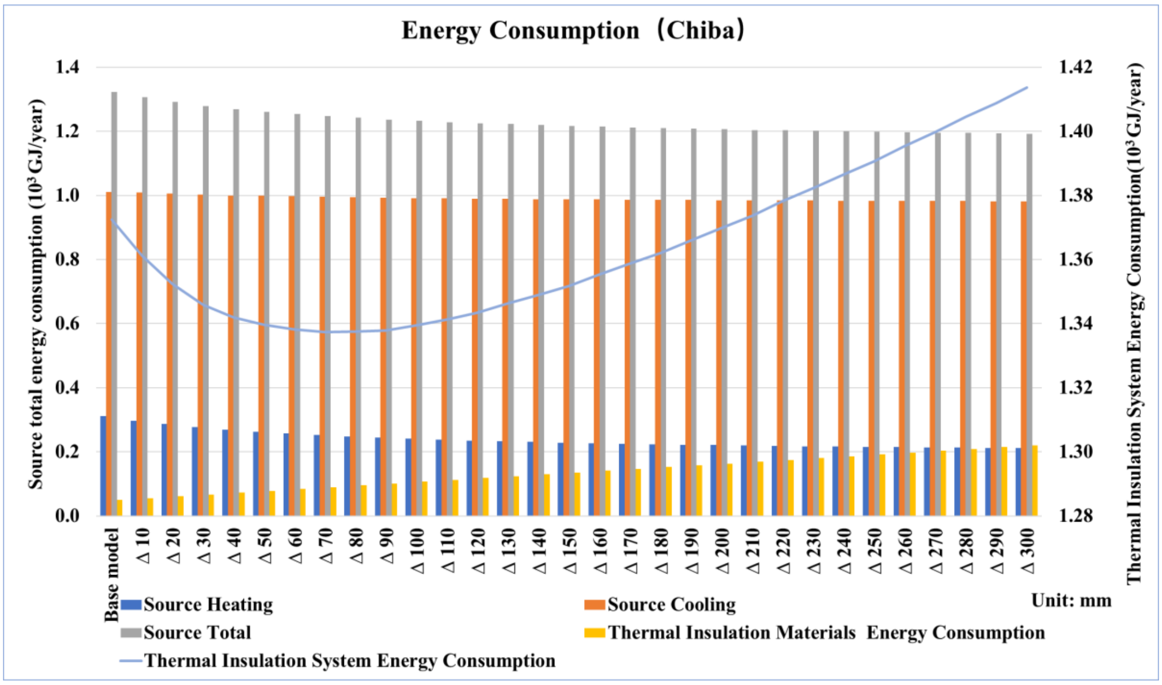

Figure 6.10 Energy consumption of the thermal insulation system in Chiba.

Figure 6.11 shows the energy consumption of Aburatsu in zone 7. The total energy consumption is higher than zone 4 and zone 5, and the cooling load is six times that of heating load. Although the general trend of system energy consumption is to decrease first and then increase, when the optimal energy consumption is reached, the thickness of the wall and roof insulation is thinner, 100mm and 165mm respectively, which is the lowest among the above-mentioned zones.

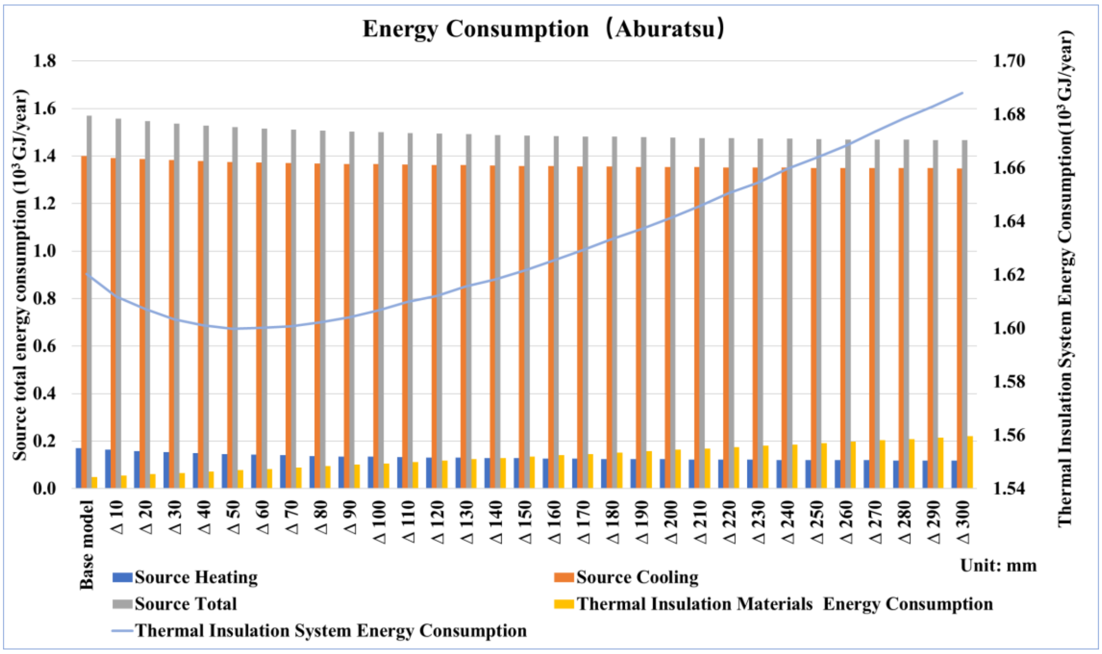

Figure 6.11 Energy consumption of the thermal insulation system in Chiba.

Through the above calculation results, it can be concluded that increasing the thickness of the insulation layer is not conducive to the energy saving of buildings that mainly rely on cooling load. From the point of view of the insulation system, in the thermal engineering zone where the cooling load is the main, the insulation material is not as thick as possible. After exceeding a certain critical value, conversely, increasing the thickness of the insulation material will increase the energy consumption of the insulation system.

6.4.3.Regional carbon emission performance of envelope insulation system

Kushiro's carbon emissions in the first thermal engineering zone are shown in Figure 6.5. The total carbon emissions of the insulation system decrease with the increase of the thickness of the insulation layer. When the wall and roof insulation thickness reach 510mm and 575mm respectively, the total carbon emission reaches the lowest value. After that, it gradually increased, but the rate of increase was slow. The thickness to achieve the lowest carbon emission is significantly higher than the thickness to achieve the lowest energy consumption.

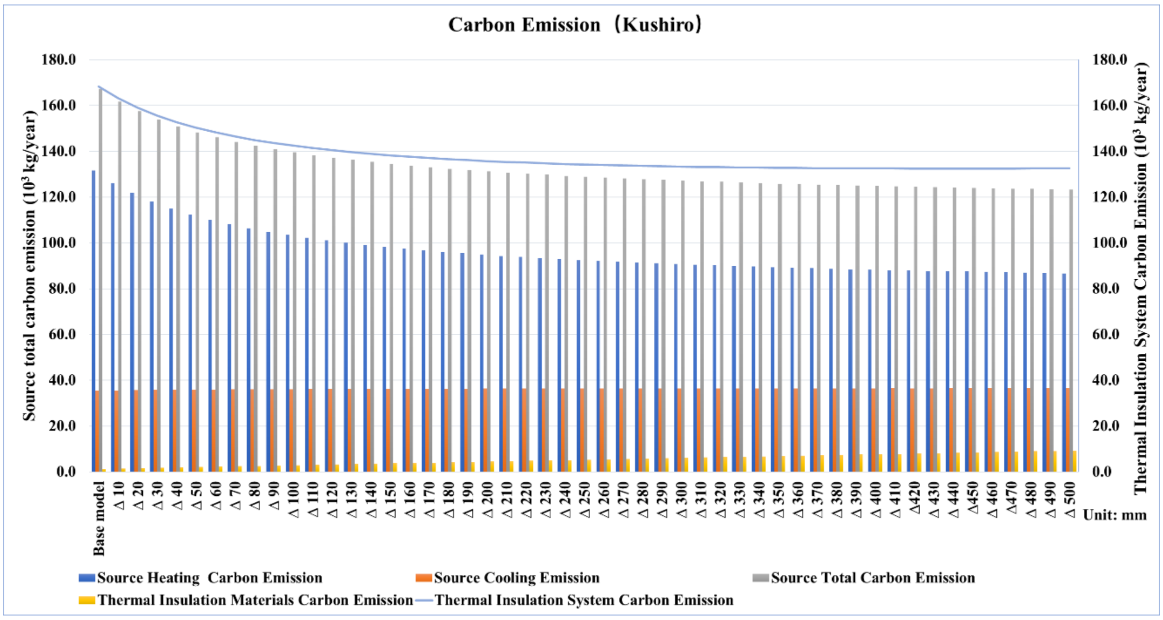

Figure 6.12 Carbon emission of the thermal insulation system in Kushiro.

Figure 6.13 shows the Tomakomai carbon emission map for zone 2. The total carbon emission of its thermal insulation system is decreased first and then increased. The system has the lowest energy consumption when the thickness of the wall and roof insulation layers are 450mm and 515mm, and the overall energy consumption of the system beyond this limit gradually increases. The difference between zone 2 and zone 1 insulation systems reaches the lowest carbon emissions. The wall and roof are both reduced by 60mm, because the cooling load of the zone 2 insulation system is reduced more, resulting in a reduction in total energy consumption, so the thickness of the insulation material is reduced more.

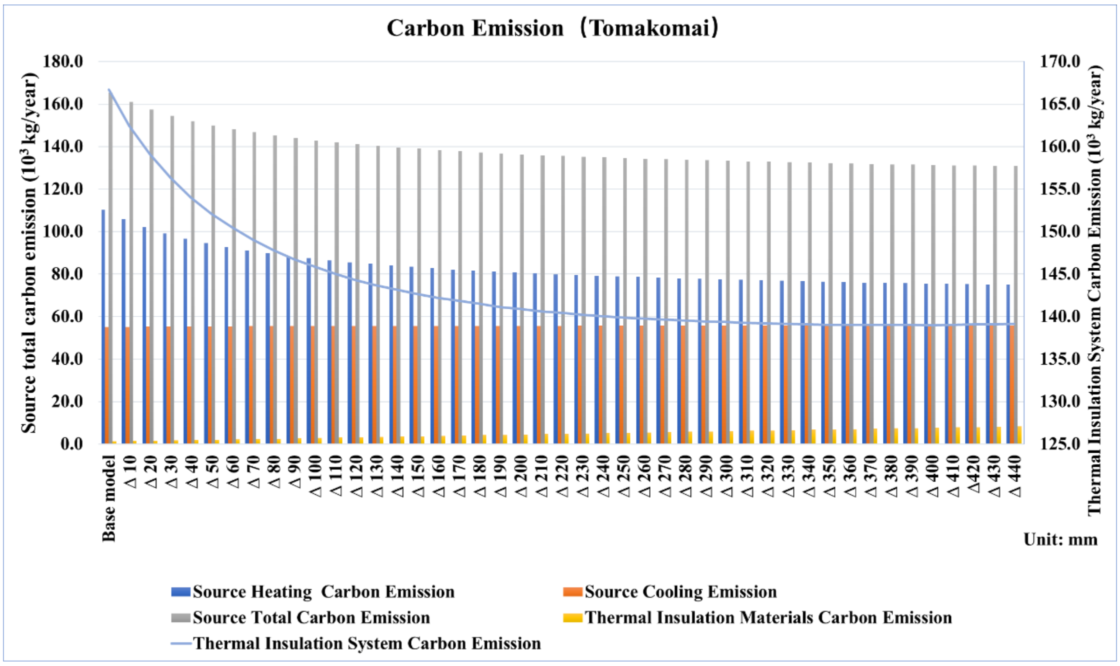

Figure 6.13. Carbon emission of the thermal insulation system in Tomakomai.

Figure 6.14 shows the carbon emission trend of the zone 3 insulation system as the thickness of the insulation layer increases. Compared with zone 1 and zone 2, when the thermal insulation system reaches the lowest carbon emission, the thickness of the thermal insulation layer of the wall and roof is 430mm and 495mm, respectively. This shows that as the cooling load of the case building continues to decrease, the thickness of its optimal insulation layer continues to decrease.

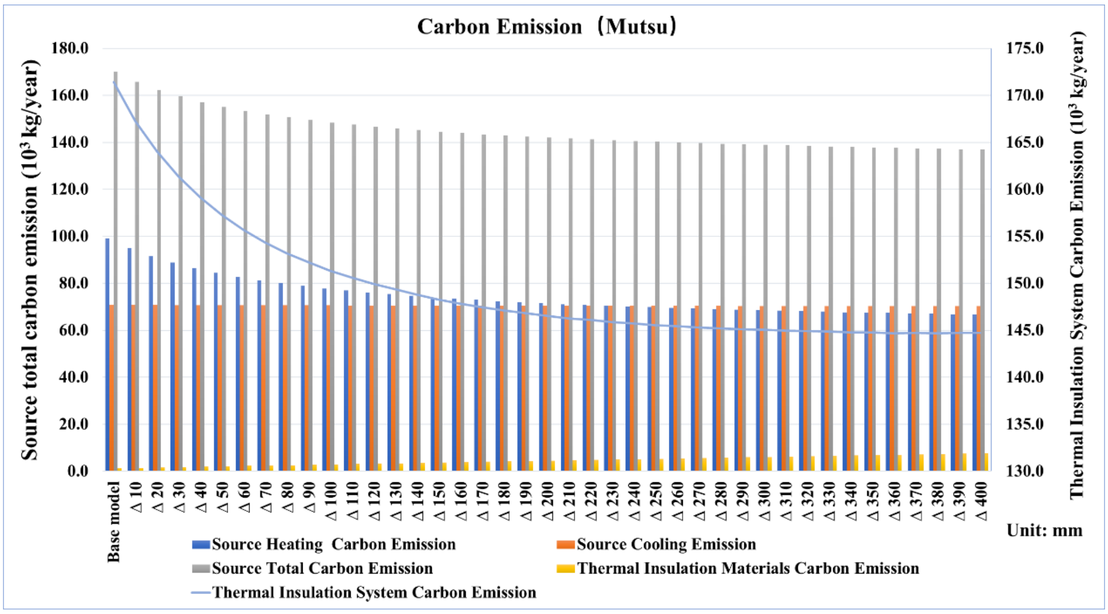

Figure 6.14 Carbon emission of the thermal insulation system in Mutsu.

Figure 6.15 shows the carbon emission trend of Sendai in zone 4. Starting from zone 4, the building is dominated by cooling load. The cooling load of zone 4 is 1.49 times that of heating load. In this case, when the thermal insulation system reaches the lowest carbon emission in the thermal engineering zone, the thickness of the thermal insulation layer of the wall and roof is 330mm and 395mm, which is a large decrease. The thickness of the insulation layer has decreased by 23% compared to zone 3.

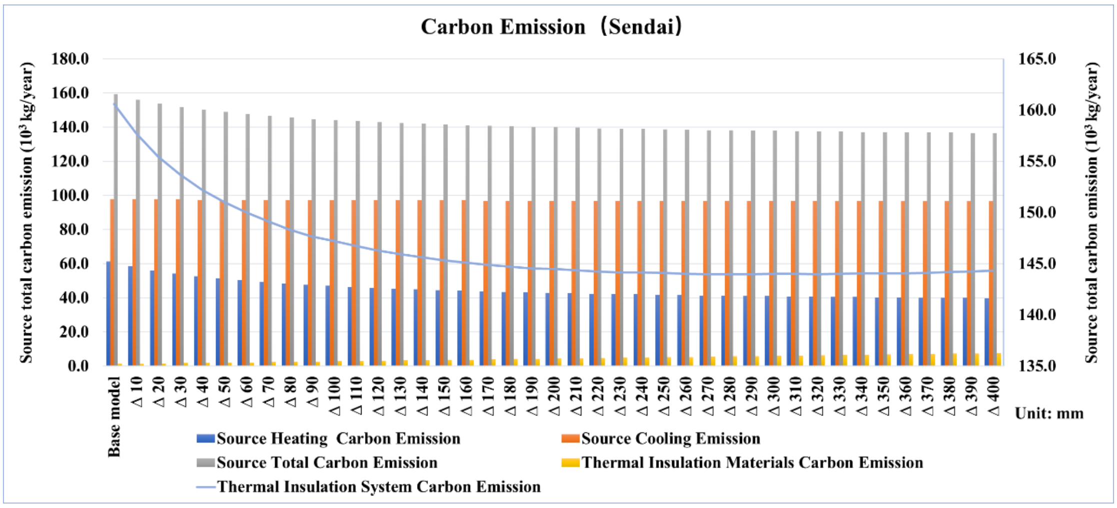

Figure 6.15 Carbon emission of the thermal insulation system in Sendai.

The carbon emission trend of Hikone's insulation system is shown in Figure 6.16. The system has the lowest carbon emission when the thickness of the wall and roof insulation is 300mm and 365mm respectively. Beyond this limit, the overall energy consumption of the system gradually increases. The optimal thickness of zone 5 is very small compared to zone 4. The reason is that zone 4 is also dominated by cooling load. For the application of potential carbon emission reduction technology, it should focus on reducing the cooling load to achieve low carbon emission of the insulation system.

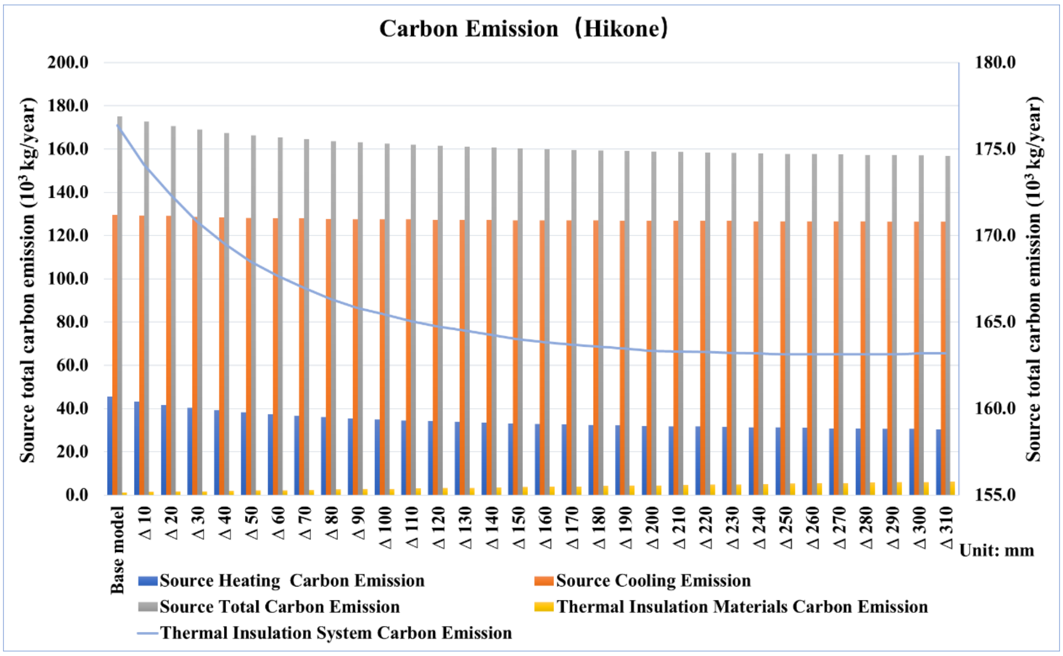

Figure 6.16 Carbon emission of the thermal insulation system in Hikone.

Figure 6.17 shows the carbon emission trend of the thermal energy consumption system in Chiba. The carbon emission law of its thermal insulation system is the same as that of zone 4 and zone 5. The system has a thinner wall and roof insulation layer, with the lowest carbon emissions at 300mm and 365mm respectively. After exceeding this limit, the carbon emissions of the system gradually increase. The best protective layers of zone 4 and zone 5 are the same because the cooling load of the two zones is not much different, and the overall energy consumption of the two zones is basically the same.

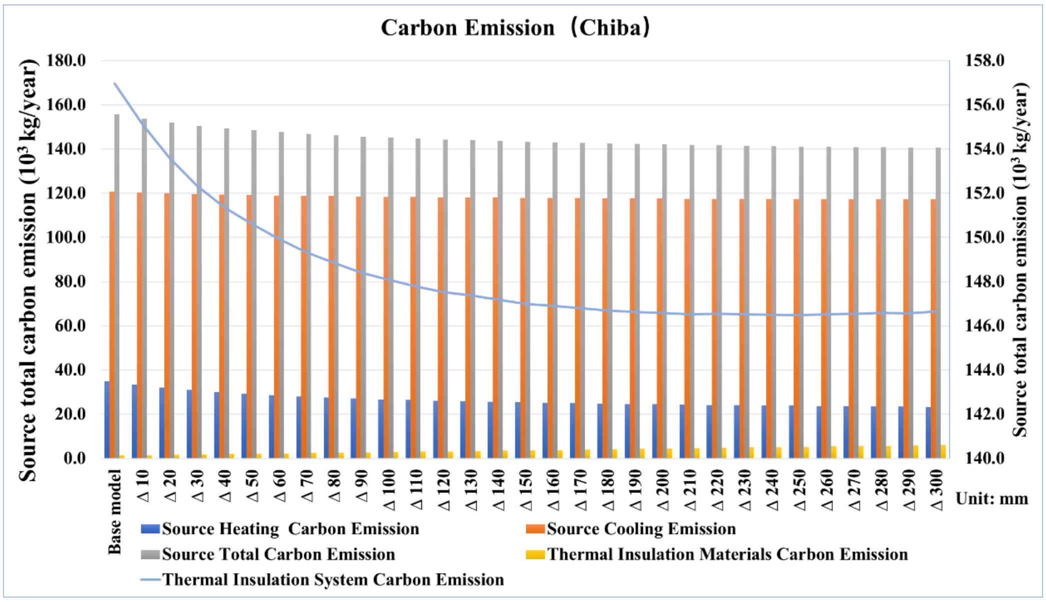

Figure 6.17 Carbon emission of the thermal insulation system in Chiba.

The carbon emissions of the insulation system of Aburatsu in zone 7 are shown in Figure 6.18. The total carbon emissions of different schemes are higher than that of zone 4 and zone 5. The trend of total carbon emissions of the system follows the law of first decreasing and then increasing. When the best energy consumption is achieved, the thickness of the wall and roof insulation is the thinnest in these seven areas, respectively 250mm and 315mm.

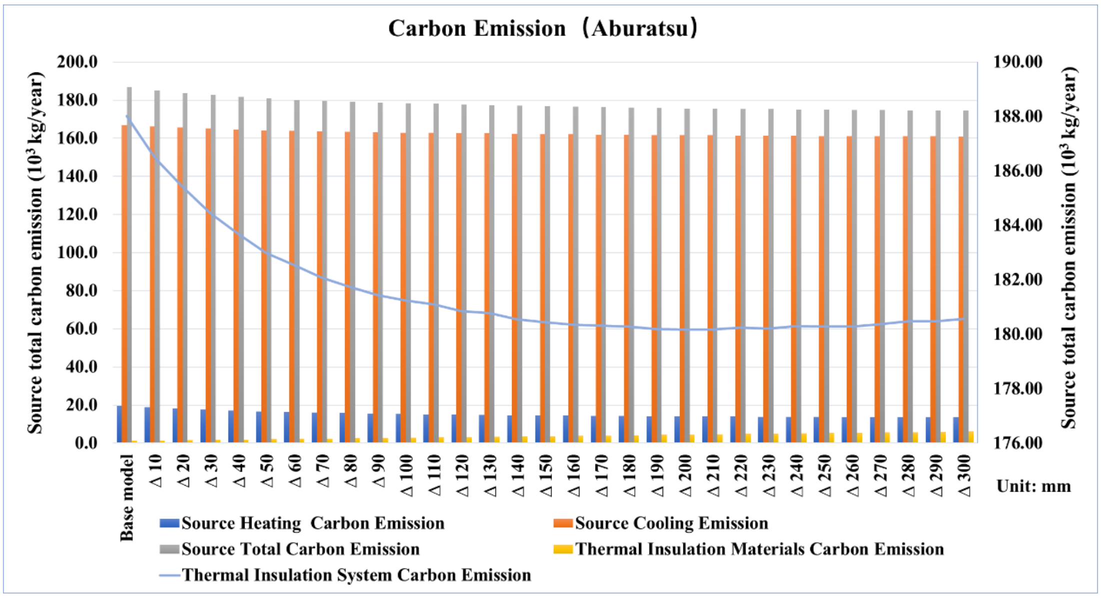

Figure 6.18 Carbon emission of the thermal insulation system in Aburatsu.

From the above analysis, it can be seen that no matter which thermal engineering zone is used, reducing the carbon emission of the insulation system should be considered from both the building energy consumption and the material energy consumption. Although simply increasing the thickness of the insulation material will reduce the energy consumption of the building operation, it will also increase the investment in energy consumption of the material. In the later period, the operating load reduction rate of the building slows down with the increase of the thickness of the insulation layer. When the thickness of the insulation layer exceeds a certain thickness, it will cause an increase in the total energy consumption. From zone 1 to zone 7, the optimal insulation layer thickness of insulation materials is gradually decreasing. Among the zones that mainly focus on heating load, there is a greater potential for reducing the energy consumption of the insulation system by increasing the thickness of the insulation layer. In zones that are mainly cold-loaded, there is less potential to increase the thickness of the insulation layer and reduce the energy consumption of the insulation system.

6.5. Summary

The above research can conclude that the optimal insulation thickness of each zone presents a similar law: the optimal insulation thickness evaluated by the environmental load index is greater than the energy consumption index. Therefore, if only the energy consumption index is considered, the best environmental load effect of the building cannot be achieved. The environmental load should be incorporated into the building design as a factor, so that the architectural plan is close to the optimal plan of the life cycle environmental load. Therefore, different minimum protective layer thicknesses should be established for different thermal engineering zones to achieve the best building load performance as possible. Zone 1 to zone 3 have greater potential for energy saving in insulation systems by increasing the thickness of the insulation layer. The effect is not obvious in zone 4 to zone 7. In these areas, it is recommended to reduce the cooling load of the building through energy conservation such as natural ventilation and shading design.

The optimal insulation layer thickness of the building in the same thermal engineering zone is different from the energy consumption calculation result and the carbon emission calculation result. The calculated value of the former is lower than the latter. This is because the contribution rate of petroleum as a raw material for thermal insulation production in energy consumption is lower than its contribution rate in environmental load. Petroleum, as a raw material for thermal insulation materials, has a greater environmental load during the disassembly stage.

The life cycle of a building is long, so all factors need to consider timeliness. The load in the building operation phase is mainly determined by the energy load and the usage habits of the personnel. As productivity increases and people's awareness of environmental protection increases, the environmental load of buildings will gradually decrease. Taking these factors into account, the amount of energy saved by increasing the thickness of the insulation will become smaller, and the optimal thickness of the insulation material will become thinner. The conclusions drawn in this section are based on specific conditions, which simplifies the impact of relevant factors on the operating load of the building, such as ignoring the effect of thermal bridges around the window, and maintenance of materials during operation. Therefore, further research is needed on how to weight related factors. However, only the specific optimal thickness of the insulation layer is affected. The trend of the above results is established and can provide a directional reference.

Reference

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2. Energy saving area classification Available online: https://www.mlit.go.jp/common/001263698.pdf (accessed on Mar 8, 2020).

Chapter 7. Conclusions

The prefabricated building has been developed for more than 100 years. It has made great achievements and become the future development direction of the construction industry. But it still faces many obstacles and challenges. As a mature evaluation theory, life cycle assessment method is currently widely used in the field of architecture. This article summarizes the development of prefabricated buildings in various countries. Combined with the historical economic background of the respective countries where the prefabricated buildings are located, the development ideas and technical characteristics of prefabricated buildings in various countries are analyzed. The purpose is to understand the concept of prefabricated buildings and provide references for the development of prefabricated buildings in other countries. By summarizing and combing the existing life cycle assessment methods, to understand the concept and method of the life cycle assessment method and construct a life cycle assessment method suitable for evaluating prefabricated buildings. The assessment of the environmental impact of a building throughout its life cycle is a necessary means to achieve targeted energy conservation and emission reduction. The study divides the life cycle of prefabricated buildings into design stage, materialization stage, use and maintenance stage, and dismantling and recycling stage. Accounted for each stage separately, to determine the impact of prefabricated buildings on the environment throughout the life cycle. The article also conducted a comparative study on prefabricated buildings and traditional buildings and analyzed the environmental impact and cost performance of the two from the perspective of the building life cycle. In addition, from the perspective of building life cycle, the optimal solution of insulation thickness of building envelope structure in different regions is analyzed. The conclusions of this research are summarized as follows.

In chapter one, **Background and Purpose of This Study**， introduced today's global issues, such as climate change, greenhouse gas emissions, population growth and accelerated urbanization, which poses great challenges to the sustainable development of human society. Among the various causes of these problems, the construction industry has been criticized as a major developer of major energy and natural resources. The global construction sector consumes 40% of the total final energy use. Buildings that account for upstream power generation account for 36% of global energy-related carbon dioxide emissions. In order to solve these problems, prefabricated construction has become the development direction of the construction industry. Prefabricated buildings are a widely accepted method used to replace traditional on-site construction methods. The advantages of prefabricated buildings are saving time, improving quality, reducing waste and reducing energy consumption. In order to clarify the impact on the environment during the entire life cycle of the prefabricated building, a life cycle analysis method is proposed to evaluate its impact on the environment.

In chapter two, **Survey on the Prefabricated Buildings Development in Various Countries**, provided a comprehensive survey of the historical and current development of prefabricated buildings in different countries. Through comparative research on the development history of prefabricated buildings in different countries, it is found that the development of prefabricated buildings in various countries is based on the increase in housing demand and large-scale housing construction. Under the encouragement and guidance of government policies, research institutions and enterprises promote the development of prefabricated buildings. The prefabricated buildings in various countries has experienced almost half a century of development and has basically reached a mature and stable period. Prefabricated buildings have become one of the main methods of housing construction in developed countries.

In chapter three, **Theories and Methodology of the Study**, investigated and analyzed the life cycle assessment methods, the definition of life cycle analysis methods is clarified, and the advantages and disadvantages of different methods are analyzed. At the same time, according to the characteristics of prefabricated buildings, build a life cycle model that conforms to the characteristics of prefabricated buildings. The simulation models are detailed introduce in this chapter as well. The climate data in this study are mainly employed TMY3 files which are derive from Integrated Surface Database (ISD) of US National Oceanic and Atmospheric Administrations (NOAA) with hourly data through 2017.The building energy consumption simulation among the 7 stations in Japan were estimated using EnergyPlus, a validated and physics-based BES program developed by the U.S. Department of Energy (DOE).

In chapter four, **Environmental and Cost Performance Comparison between Prefabricated and Traditional Buildings**, assess the environmental impact of prefabricated buildings and traditional cast-in-situ buildings over the building life cycle using a hybrid model. A case study of a building with a 40% assembly rate in Japan was employed for evaluation. The comparative analysis of the environmental and environmental impacts and cost differences of the two buildings during their entire life cycle, as well as the impact of different assembly rates and precast pile foundations on the environment. It concluded that the total energy consumption, and carbon emissions of the prefabricated building was 7.54%, and 7.17%, respectively, less than that of the traditional cast-in-situ building throughout the whole life cycle. The carbon emissions reduction in the operation phase reached a peak of 4.05 kg CO_2/year·m^2. The prefabricated building was found to cost less than the traditional cast-in-situ building, reducing the price per square meter by 10.62%. The prefabricated building has advantages in terms of reducing global warming, acid rain, and health damage by 15% reduction. With the addition of the assembly rate, the carbon emissions and cost dropped, bottoming out when the assembly rate was 60%. After that, an upward trend was shown with the assembly rate increasing. Additionally, this study outlined that the prefabricated pile foundations is not applicable due to its high construction cost and environmental impact.

In chapter five, **Environmental Performance of Envelope Insulation in Prefabricated Building**, proposed models for the thermal insulation system of prefabricated buildings and traditional cast-in-situ buildings, according to the characteristics of the two buildings at different stages. The process analysis method is used to compare the environmental impacts of the two building thermal insulation systems during their life cycle, and to provide references for the development of effective emission reduction measures for carbon emission levels at different stages.

In chapter six, **Regional Applicability and Cost Performance of Envelope Insulation in Prefabricated Buildings**, the energy consumption of the insulation materials in the production process and the reduction of the energy consumption of the air conditioner by increasing the thickness of the insulation layer are comprehensively considered according to the division of the life cycle of the insulation system in Chapter 5. Based on different thermal climate zones in Japan, the relationship between the thickness of the insulation material in each zone and the energy consumption of the air conditioning was analyzed. The study found that the thickness of the insulation layer will reduce the energy-saving effect of the building when it exceeds a certain value. The optimal insulation layer thickness for different thermal engineering zones is given.