Impact of Fixed External Shading Devices on Green Educational Building Assessment in Hot Summer and Warm Winter Climate

by

Danxia Qiu

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Abstract

The construction industry contributes a significant part of global energy consumption and carbon emissions. Accurately calculating and evaluating the energy consumption, economic performance, and carbon emissions regarding various types of building components is important for the energy efficiency structural design and building sustainable development. The use of external shading devices can effectively control daylight and solar heat, maintain thermal and visual comfort, especially reducing energy consumption for cooling system. Although great improvements have been achieved in 'Assessment Standard for Green Building GB/T50378-2019' (ASGB-2019), the current implemented Chinese green building evaluation standard, issues may have significant consequences on the implementation of new policy. The impact of fixed external shading facilities on their thermal and energy-saving performance has been highlighted in the existing research, however, their economic and environmental performance haven't been in study. Moreover, there is a lack of effective assessment method for the fixed external shading devices focusing on their multiple performance (energy-saving, economic and environmental perspectives) in ASGB-2019.

To investigate the impact of fixed external shading devices on green educational building within the hot summer and warm winter climate region of China, the mixed research methodology has been applied in this research project, integrating various quantitative and qualitative approaches. The qualitative measures include literature review and case study, while the quantitative approaches are comparative study and simulation analysis methods. The BESI 2024, life cycle cost analysis (LCCA), CEEB 2024 and ÉLimination Et Choix Traduisant la REalité (ELECTRE) I method have been adopted as simulation analysis methods.

The main findings are: 1) The comparative study and case study results point out that there is a low focus on the assessment of external shading design and a lack of qualitative or quantitative regulatory provision on the assessment of fixed external shading devices in ASGB-2019, establishing a foundation for introducing the multi-criteria decision analysis (MCDA) method in the subsequent study. 2) The energy-saving simulation results generate an optimum shading option among 21 proposed fixed external shading designs, which is 'Integrated shading I' with 6.03% of energy-saving rate of building envelope. 3) By considering energy-saving effect and three recyclable materials (e.g., merbau, aluminum, and polycarbonate), the LCCA results show that the six targeted shading cases with net present value (NPV) of life cycle cost (LCC, also can be regarded as initial investments) from high to low are Polycarbonate A, Merbau A, Polycarbonate B, Merbau B, Aluminum A and Aluminum B. 4) The carbon emission simulation results demonstrate the six shading alternatives with life cycle carbon ($LCCO_2$) emission values from high to low are Aluminum B, Aluminum A, Polycarbonate A, Polycarbonate B, Merbau A and Merbau B. 5) Integrating the entropy weight and ELECTRE I methods, the MCDA result generates a final ranking table to suggest a most preferred shading option for the studied education building, which is Aluminum B. Further, a weighting matrix with three criteria has been proposed for the assessment improvement regarding fixed external shading devices, namely, 'energy-saving rate of building envelope', 'NPV of LCC', and '$LCCO_2$ emission amount', with the weight coefficient of 32.8%, 28.7% and 38.5% respectively.

This research proposes a mixed methodology to support MCDA method on the assessment of fixed external shading devices with consideration of energy-saving, economic and environmental impact. A green educational building project is presented to demonstrate the use of the proposed methodology and provide a useful reference for the improvement of green building assessment in China.

Keywords: Green building assessment, fixed external shading, energy-saving, LCCA, $LCCO_2A$, MCDA

Table of Contents

List of Figures

List of Tables

List of Acronyms/Abbreviation

AHP	Analytic hierarchy process
ASGB-2014	Assessment Standard for Green Building GB/T 50378-2014
ASGB-2019	Assessment Standard for Green Building GB/T50378-2019
BCA	Building and Construction Authority
BCECG	Building Carbon Emission Calculation Guidelines (Trial)
BEE	Building Environmental Efficiency
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CABR	China Academy of Building Research
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CA	Cluster Analysis
COPRAS	Complex Proportional Assessment
DCEEPB-2018	Design Code for Energy Efficiency of Public Buildings SJG 44-2018
DGNB	Deutsche Gesellschaft fur Nachhaltiges Bauen
DOHURD-GD	Department of Housing and Urban-Rural Development in Guangdong Province
DSEEPB-2015	Design Standard for Energy Efficiency of Public Buildings GB50189-2015
DSEEPB-GD-2020	Design Standard for Energy Efficiency of Public Buildings in Guangdong Province DBJ 15-51-2020
ELECTRE	ÉLimination Et Choix Traduisant la Realité
EP	Exploitation procedure
ESGB-2006	Evaluation Standard for Green Building GB/T 50378-2006
EVAMIX	Evaluation of Mixed Data
GB Tool	Green Building Tool
GCEEREAB-2021	General Code for Energy Efficiency and Renewable Energy Application in Buildings GB55015-2021
GHG	Greenhouse gas
GSBC	German Sustainable Building Council
HVAC	Heating Ventilation and Air Conditioning
ICE	Institution of Civil Engineers
IISBE	International Initiative for a Sustainable Built Environment

IEQ	Indoor environmental quality
JSBC	Japan Sustainable Building Consortium
LCA	Life cycle assessment
LCC	Life cycle cost
LCCA	Life cycle cost analysis
$LCCO_2$	Life cycle carbon
$LCCO_2A$	Life cycle carbon emission assessment
LCEA	Life cycle energy assessment
LCI	Life cycle inventory
LCT	Life cycle thinking
LEED	Leadership in Energy and Environmental Design
LP	Linear Programming
MADM	Multiple attribute decision making
MCAP	Multi-criteria aggregation procedure
MCDA	Multi-criteria decision analysis
MODM	Multi-objective decision making
MOHURD	Ministry of Housing and Urban-Rural Development
MAUT	Multi Attribute Utility Theory
MDA	Multivariate Discriminant Analysis
NABERS	National Australian Built Environment Rating System
NPV	Net present value
PCA	Principal component analysis
PCMs	Phase change materials
PV	Present value
SBCEC-2019	Standard for Building Carbon Emission Calculation GB/T 51366-2019
SBEPC-2012	Standard for Building Energy Performance Certification JGJ/T 288-2012
SBRS	Sustainable Building Reporting System
SMBHC	Shenzhen Municipal Bureau of Housing and Construction
SMAA	Scoring Multi-Attribute Analysis
SGPCCB-2018	Standard for Green Performance Calculation of Civil Building JGJ/T 499-2018

SRIBS	Shanghai Research Institute of Building Sciences
TDCCB-2016	Thermal Design Code for Civil Building GBT50176-2016
TOPSIS	Technique for Order Preference by Similarity to Idea Solution
UDI	Useful daylight illuminance
USGBC	U.S. Green Building Council
WPM	Weighted Product Method
WSM	Weighted Sum Method

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Chapter 1. Introduction

1.1.Background

As a country with high energy consumption, building energy consumption accounts for a relatively high proportion of the total energy consumption in China (Qiang *et al.*, 2015). This is because China is currently in the peak period of old city renovation and new city construction. The rapid development of urban construction has promoted the rapid development of the construction industry, which inevitably caused a large amount of energy consumption and waste (Zhang, 2015). At present, energy is becoming increasingly scarce, and the energy-saving design of buildings has become a research hotspot in the entire construction field. As one of the important measures for building energy conservation, the external shading technology can effectively reduce indoor radiation heat gain. Consequently, lower the energy consumption of the cooling systems in summer, especially in the hot summer and warm winter climate region. The cooling devices are being used frequently and covering most of time in summer, resulting in the higher power consumption of cooling system compared with other climate regions in China. Improper external shading design will affect the needs of the normal indoor lighting and the indoor solar radiation heat gain in winter (Yang, 2019). As an important part of the building's external envelope structure, the external shading devices and components can effectively block the sunlight from entering the room through the window glass, thereby improving the comfort of the indoor thermal environment and light environment. At the same time, it can also use architectural construction technology to create a virtual facade and better optimize the building shape (Liu, 2015). In addition, as a passive energy-saving measure, the external shading technology requires less initial investment and has a more obvious energy-saving effect, compared with other technically complex passive energy-saving measures.

Various types of shading devices have provided energy saving benefits for buildings. The external shading forms are commonly seen on protrusion (Lee and Tavil, 2007). For the roller blinds (Tzempelikos and Athienitis, 2007) and venetian blinds (Simmler and Binder, 2008), studies have been conducted from external, intermediate to internal. Bellia et al. (2014) roughly classified the solar shading systems as fixed shading devices, adjustable shading devices and other types. Although the internal solar shading devices are quite effective on glare reduction, they have little contribution to the thermal comfort of a building as they block the incoming radiation only after the sunlight has penetrated the glazing. In contrast, the external shading facilities can block direct solar radiation through windows, reducing heat transfer within the buildings and thus can help with thermal comfort adjustment as well as glare reduction (Kim *et al*., 2012; Khoroshiltseva *et al*., 2016). Therefore, in the early stages of building design, it is an important aspect for architects and designers to consider how to choose the appropriate shading device and its corresponding assessment methods.

As the awareness of the importance regarding the external shading facilities continues to increase in all walks of life, a large number of researchers have begun to conduct a series of studies on the impact of external shading facilities on the energy-saving effect of buildings (Liu, 2010; Wan, 2012), indoor thermal and humid environment (Yang *et al*., 2016; Wang, 2021), lighting effect (Wang, 2020; Jiang, 2021), visual effect (Zhang, 2016; Jiang, 2020), ventilation effect (Liu, 2011; Wang, 2013), etc. In addition, some Chinese architects have also begun to apply the external shading design during the building design stage. However, some researchers aware that the external shading facilities are designed to meet the needs of architectural modelling rather than the purpose of energy-saving effect. Due to its low construction cost, the fixed external shading design is currently widely used in buildings in major cities of China. Yang (2019) conducted the energy-saving and lighting simulation by using the software of BESI 2018 and DALI 2018 based on the GBSWARE platform to explore the energy-saving and lighting effects of the fixed external shading devices in the office building located in city of Nanchang. Wang (2013) conducted field measurement and simulation by using Ecotect and Phoenics to explore the effects of solar radiation, lighting, and ventilation regarding four types of fixed external shading devices. This research was carried out in the educational buildings of three universities located in Guangzhou higher education mega center. This specific area belongs to hot summer and warm winter climate region in China. However, the investment cost and the environmental impact of a series of fixed external shading designs have not been deeply studied and analysed in the above research. This can be largely attributed to the difficulty in cost data collection regarding the external shading facilities, the hardness of determining the economic and environmental assessment methods and corresponding criteria. It has proven that there is a lack of awareness among researchers about the economic and environmental impact regarding the fixed external shading equipment on the overall building. Meanwhile, the above studies infer that there is a gap in the literature related to comprehensive or multi-criteria assessment methods regarding the fixed external shading devices, from the perspective of energy efficiency, economy, and environment.

Since the concept of green buildings began to spread, relevant government departments in China have successively promulgated a series of specifications and standards for energy-saving building design. The current standard for evaluating green buildings in China is the 'Assessment Standard for Green Building GB/T50378-2019' (Hereinafter referred to as ASGB-2019) which promulgated by the Ministry of Housing and Urban-Rural Development (Hereinafter referred to as MOHURD). However, it is worth noting that ASGB-2019 has not yet formulated corresponding evaluation regulations and scoring methods for the fixed external shading facilities, and thus cannot directly reflect the energy-saving impact of them on buildings in the green building assessment report, let alone their initial investment amount and environmental impact.

Due to the growing awareness among the architects about the energy-saving effects of the external shading design on buildings, it is very crucial for the government departments and relevant green building evaluation policy makers to consider the importance of assessing the fixed external shading devices through improvement of ASGB-2019 in a better manner. The existing literature on green building evaluation reveal that there are many challenges and barriers which prevent policy makers and government officers to effectively implement the assessment standards. In addition to defining and quantifying the challenges faced by the Chinese building industry in the green assessment process, the current sustainability assessment practices are commonly based on the thermal effects of buildings, which obviously overlooks the practicality of multi-criteria comprehensive assessment during the building design decision-making process. A good way to improve the assessment methods is to establish quantitative terms to qualify the concept of multi-criteria comprehensive assessment and incorporate it into the early stages of the project development process to guide decision-making as progress is made. For green building structural engineers, there is usually a lack of tools specifically used to describe multi-criteria comprehensive assessment to provide information for making design decisions. These problems need to be further explored, especially in-depth investigation in green building assessment practices. Challenges and barriers that encountered by Chinese government is to be examined in this research. As the awareness of assessment method issues increased, e.g., regulatory provision, scoring methods, weighting system, etc., it is expected to influence the implementation of green building evaluation standards. This research is also to examine these internal issues and focus on the roles of key actors in the assessment practice of green building.

This research will address the aforementioned research gap on the impacts of fixed external shading devices and explore the relevant issues of the evaluation standard. Through examining of the research problem, the situation regarding the assessment of fixed external shading facilities with respect to green building in Chinese construction industry can be improved, as this research will uncover some of the implications for the evaluation sector. The contributions of this research are both theoretical and empirical. From a theoretical perspective, the information contained in the literature review has identified the aspects of external shading facility assessment that deserve further consideration from energy-saving, economic, and environmental point of view. This has also shed light on the process green building assessment practices based on a real construction case that is lacking in the previous research. The empirical results of this study will explore these issues in more detail.

1.2.Research motivation

The construction industry is of high economic significance with crucial impacts on the environment and society (Burgan and Sansom, 2006). As a major consumer of renewable and non-renewable natural resources, the construction industry is an active producer of pollutants and waste (Ding, 2008). Inevitably, the concern about how to ease these impacts through the concept of green and sustainable construction is increasing in the building industry. A comprehensive criteria assessment in the construction sector may be a more reliable solution.

The awareness of the need for sustainability is increasing in the building sector. This requires balancing the energy consumption, economic, environmental, and social benefits of the industry with the adverse effects on the present and future generations. In one of the priority actions of the Institution of Civil Engineers (Hereinafter referred to as ICE) towards a green economy, structural engineers are required to participate in projects at the initial stage and contribute to balancing capital investment and operational carbon emissions to lower the emission amount throughout the building life cycle (Oti, 2014). Therefore, solutions regarding greenhouse gas (Hereinafter referred to as GHG) emission reduction and other building performance optimization techniques such as energy consumption analysis, life cycle cost (Hereinafter referred to as LCC) and life cycle carbon (Hereinafter referred to as $LCCO_2$) emissions, constitute efforts to achieve sustainable development. These efforts are increasingly based on information technology to keep pace with the contemporary developments in the world. Furthermore, contemporary information systems are showing a trend towards more effective and efficient performance as they are the product of continuous improvement through research (Dawood and Sikka, 2009). The selection of the best design solution before conducting detailed building design and construction commences can maximize resource savings in infrastructure projects. Therefore, it is essential to develop an advanced assessment method for the project evaluation stage to assist in the investment decisions regarding building external shading design. These premises constitute the main motivation for this research work. The research area of sustainability, green building assessment, external shading design assessment, multi-criteria assessment and building simulation analysis, etc., will be included in this study.

1.3.Aims and objectives

This research aims to investigate the impact of the proposed fixed external shading devices on green educational building assessment, considering three specific criteria from energy conservation, economic, and environment point of view. A multi-criteria decision analysis (Hereinafter referred to as MCDA) method is introduced to assist the assessment for a real green educational building project located in hot summer and warm winter climate region in China. This is targeted at quantifying the multi-criteria assessment of fixed external shading design alternatives at the building conceptual design stage, to further provide the Chinese stakeholders of architectural design, green building assessment, and standard policy development with the improvement recommendations related to the assessment of fixed external shading facilities in ASGB-2019. To achieve the overall aim, the research objectives have been set as follows.

- Investigate the development and actual implementation problem of external shading-related provisions in three versions of Chinese green building evaluation standards.
- Assess the energy-saving impact of various fixed external shading designs on the green educational building in Shenzhen by using energy conservation simulation software of BESI 2024.
- Assess the initial investment of the fixed external shading devices on the studied green educational building in Shenzhen by life cycle cost analysis (Hereinafter referred to as LCCA).
- Carry out the life cycle carbon emission assessment (Hereinafter referred to as $LCCO_2A$) of the fixed external shading devices on the studied educational building in Shenzhen by using carbon emission simulation software of CEEB 2024.

- Conduct MCDA of six fixed external shading devices on three specific assessed criteria for the studied green educational building in Shenzhen by using ELECTRE I.

1.4.Brief methods

A variety of research methods have been applied in this work. To achieve the stated objectives, a series of quantitative and qualitative approaches have been used, such as case study, software simulations, and comprehensive assessment method. In the first stage of the research work, a review of relevant literature in the research field has been conducted. It has been further used as a tool to determine the appropriate methods to achieve the set objectives in stages.

To achieve the first objective, a comparative study has been applied in two stages by reviewing relevant evaluation standards. The case study of a green educational building project located in Shenzhen has been carried out. This is to explore the whole process of green building evaluation and the accurate assessment situation of external shading design in Chinese building industry.

To achieve the second objective, a building energy-saving simulation study by using BESI 2024 has been carried out, based on the aforementioned green educational building project. This is to obtain the various construction parameters and input dimension values of the proposed external shading designs. A comparative study regarding the energy-saving assessed criteria for 21 shading options has been conducted, in order to determine the optimum shading design.

To achieve the third objective, document survey has been carried out with the local external shading product manufacturers, material suppliers and renewable resource recycling companies to collect the product information and cost data at different life cycle stages. LCCA has been conducted for 50 years regarding the six fixed external shading devices based on the studied education building. A comparative study has been performed amongst the six shading cases regarding their corresponding costs at each life cycle stage. The initial investments of the targeted shading options have been estimated from high to low through further comparison.

To achieve the fourth objective, a building carbon emission simulation study has been carried out based on the studied educational building by using CEEB 2024. A comparative study has been conducted amongst six external shading options regarding their corresponding carbon emission amounts at each building life cycle stage. This is to generate the optimum case with lowest carbon emission amount through further comparison.

To achieve the fifth objective, the entropy weight method has been used through a series of formulas calculations in Excel spreadsheet, to determine the weight coefficients for the assessed criteria. The XLSTAT 2022 plug-in in the Excel spreadsheet has been used for supporting ELECTRE I method calculation. This is to automatically generate a ranking table for the evaluation alternatives. The preferred shading solution has been obtained and a weighting matrix for assessing the fixed external shading devices has been delivered.

1.5.Structure of thesis

This thesis is made up of nine chapters and appendices. A basic outline of the research structure and corresponding description will be given as follows.

Chapter 1: Introduction

The important foundation and the basic information about the research are presented in this introduction chapter. The general background and the research motivation are discussed. Further, the aims and objectives, brief methods of the whole thesis are demonstrated.

Chapter 2: Literature Review

In this chapter, relevant literature on green building assessment, external shading assessment and multi-criteria decision analysis have been reviewed, to identify the research gap and challenges in this specific area.

Chapter 3: Methodology

In this chapter, the methodology that used in the whole research project is presented, including literature review, comparative study, case study, building energy-saving simulation, life cycle cost analysis, life cycle carbon emission assessment, ELECTRE I method.

Chapter 4: Comparative Study of Green Building Evaluation Standards in China-with a Focus on External Shading Related Provisions

In this chapter, the versions of ‘Evaluation Standard for Green building GB/T 50378-2006’ (Hereinafter referred to as ESGB-2006), ‘Assessment Standard for Green building GB/T

50378-2014’ (Hereinafter referred to as ASGB-2014) and ASGB-2019 are compared, including general content, detailed information with respect to the external shading related provisions. A case study of a green educational building within hot summer and warm winter climate region is adopted to present the whole process of green building evaluation in China. The problems existing in the external shading policy of ASGB-2019 has been further investigated.

Chapter 5: Energy-saving Impact Assessment

In this chapter, a Chinese local building energy simulation software named BESI 2024 is used to assess the energy-saving impact of the 21 fixed external shading designs on the green education building. An optimum shading strategy with highest value of energy-saving rate of building envelope is then obtained through simulation and comparative analysis.

Chapter 6: Initial Investment Assessment

In this chapter, the LCCA method is applied to assess the initial investment values regarding the proposed six fixed external shading devices, integrating two dimensions of the base external shading design and the optimum shading strategy which obtained by the simulation of BESI 2024 in Chapter 5, as well as three specific recyclable shading materials. Through the calculation of LCC and net present value (Hereinafter referred to as NPV), the initial investment values from high to low regarding the six fixed external shading devices based on the studied building are obtained.

Chapter 7: Life Cycle Carbon Emission Assessment

In this chapter, a Chinese local building carbon emission simulation software named CEEB 2024 is adopted to assess the environmental impact of the six proposed fixed external shading devices. The respective CO_2 emission amounts are automatically generated through simulation, and the $LCCO_2$ emission amounts of the six shading cases are then obtained through calculation. Comparative analysis of the CO_2 emission amounts regarding the studied shading cases generate an optimum one with the lowest $LCCO_2$ emission value.

Chapter 8: Multi-criteria Decision Analysis (MCDA)

In this chapter, an XLSTAT 2022 plug-in in the Excel spreadsheet is used to support ÉLimination Et Choix Traduisant la REalité (Hereinafter referred to as ELECTRE) I method calculation, to perform MCDA method for the six fixed external shading devices. The decision matrix regarding six shading alternatives on three assessed criteria is constructed for calculation of entropy weight and ELECTRE I methods. The weight coefficients for the assessed criteria are generated and the final ranking table of the six alternatives is obtained. The aluminum made devices are demonstrated to be the preferred choice when considering the external shading design for the studied educational building. Suggestions for the provision's improvement regarding the fixed external shading design in ASGB-2019 are given.

Chapter 9: Conclusion and Recommendations

In this chapter, the main research findings, contributions to knowledge, limitations and further work are presented in this chapter.

1.6.Contributions

This research contributes to the literature as it focuses significantly on the practice of green building assessment, especially the comprehensive assessment of fixed external shading devices, which shows that the researcher tries to narrow the gap in the literature highlighted by previous scholars. In addition, in terms of research background, previous studies mainly focused on the improvement measures of Chinese green building assessment system. However, most of them are comparative studies with respect to general contents of green building evaluation standards in various countries. This research focuses on the longitudinal development regarding the three versions of Chinese green building evaluation standards, and the assessment provision of fixed external shading design in the above national assessment standards, which have not been in study before. This research is also valuable to industry practitioners as it has investigated the process and the issues of Chinese green building assessment practice. It has been found that the assessment of fixed external shading design being overlooked in the current evaluation standard, even though it is known to be a low cost and high energy efficiency passive building technology.

Through a series of quantitative and qualitative approaches, such as case study, comparative study, software simulations, and multi-criteria assessment method, the novelty of this research project lies in putting forward a MCDA method based on ELECTRE I for comprehensive multi-criteria assessment of the fixed external shading devices for green building assessment practice. The contribution of this research is to propose a new assessment method and policy development direction for the fixed external shading devices in Chinese green building evaluation system. This is also to provide theoretical and practical technical guidance for the development of green energy-saving buildings, energy conservation and building carbon emission reduction in the future. It is hoped that this research work can serve as an example for research projects relevant to the involved green building consulting companies and green building evaluation agencies.

Chapter 2. Literature Review

This chapter presents the review of relevant literature on green building assessment, external shading assessment and multi-criteria decision analysis. It examines the research papers, reports and national standards on these subjects. This chapter concludes with an attempt to outline the challenges faced by multi-criteria decision support tools in informing the assessment of fixed external shading designs in the contemporary green building evaluation process in China.

2.1. Green building assessment

2.1.1. The concept of green building

According to the European Association of Architects, energy consumption in the entire process of construction accounts for 50% of total energy. For example, the cement used in construction process consumes large amount of energy, from being made into commercial concrete or building materials by manufacturers, to being used in building construction and operation. Known as ecological building and sustainable building, green building has been internationally defined as a building that provided a healthy and comfortable activity space for humans, while making the most efficient use of resources and minimizing the impact on the environment (Li, 2008). Began to be introduced into China at the end of 1980s, the concept of green building reflects the original intention of environmental protection, energy saving and harmonious coexistence. The connotation of green building has been continuously extended with the continuous intensification of environmental problems. In the context of China, the concept of green building has been defined in ASGB-2019 which issued by MOHURD, referring to saving resources, protecting the environment, reducing pollution, providing people with healthy, applicable, and efficient space throughout its life cycle, as well as maximizing the realization of high-quality architecture in harmonious coexistence between human and nature (MOHURD, 2019a).

2.1.2. The importance of green building assessment

The awareness of building energy efficiency, as well as the rational use of sunlight, air, water resources, etc., presents the balanced relationship between human beings' demands and rewards from nature (see Table 2.1). The issues of temperature, daylighting, noise reduction, energy saving, air quality, etc., have been carefully considered during the construction of green building, to achieve the goals of natural ventilation, green environment, internal and external balance as much as possible (Zhang, 2010). The green building evaluation system is a set of evaluation and certification systems applied in the overall life cycle of green buildings. By establishing a series of criteria systems, it provides specific and clear regulations for various aspects to guide the practice of green buildings. (Duan, 2007) highlighted that the assessment of green buildings can provide certain specifications and standards within the market, encourage and promote excellent green buildings, to achieve the purpose of regulating the building market. The implementation and promotion of green buildings in the practical field depends on the establishment of a clear green building evaluation system. This evaluation system can provide green buildings with systematization, modeling, and quantification of the entire process including decision-making, planning and design, implementation and construction, management, and usage. It is a decision-making and problem-solving method that combines qualitative and quantitative analysis. Since the green building evaluation system involves a wide range of professional fields, it requires the cooperation of experts from multiple fields and a set of scientific evaluation methods as technical support for policy implementation and operation.

Table 2.1 The focus of green building evaluation in different countries

Evaluation system	Evaluation object	Focus of evaluation
BREEAM (UK)	Office buildings	Energy, transportation, pollution, materials, water, land use
LEED (US)	Commercial (office) buildings	Sustainable building sites, water resources utilization, building energy conservation and atmosphere, resources and materials, indoor air quality
GBC (Canada)	New and renovated buildings	Environmental sustainability, environmental load, indoor air quality, maintainability, economy, operation management
NABERS (Australia)	New and renovated buildings	Biodiversity, main energy conservation, greenhouse gas emissions, indoor air quality, resource conservation, site planning
CASBEE (Japan)	New and renovated buildings	Quality, indoor environment, energy, resources, and materials
HK-BEAM (Hong Kong)	New and existing buildings	Site, materials, energy, water resources, indoor quality environment
ASGB (China)	Civil buildings	Energy saving, water saving, material saving, land saving, environmental protection, meet building functional requirements

2.1.3. Green building evaluation systems

The evaluation standards for green buildings encourage the use of advanced construction technology, construction equipment and construction techniques, combining the effective energy-saving materials and products, to ensure the efficiency of energy use such as thermal insulation, heating, ventilation, lighting, hot water (Gao, 2016). In 1990, the UK government launched the Building Research Establishment Environmental Assessment Method (Hereinafter referred to as BREEAM), which is the earliest green building assessment and certification system in the world. Since then, various countries have successively launched their own green certification system, among which the Leadership in Energy and Environmental Design (Hereinafter referred to as LEED) in the US has the most extensive influence, followed by the National Australian Built Environment Rating System (Hereinafter referred to as NABERS) in Australia, the Comprehensive Assessment System for Built Environment Efficiency (Hereinafter referred to as CASBEE) in Japan, the Deutsche Gesellschaft fur Nachhaltiges Bauen (Hereinafter referred to as DGNB) in Germany, Eco Profile in Norway, ESCALE in France, and ASGB in China. In addition, some international evaluation systems are also playing an important role, such as the Green Building Tool (Hereinafter referred to as GB Tool) evaluation system issued by the International Initiative for a Sustainable Built Environment (Hereinafter referred to as IISBE). With the continuous development of green building practices in various countries, the assessment tools have shifted from qualitative assessment to quantitative evaluation from the single performance evaluation to the comprehensive assessment of environmental, economic, and technical performance. The formulation, promotion and application of these evaluation systems have played an important role in advocating the concept of "green" in urban construction, guiding builders to pay more attention to the green and sustainable development.

(1) BREEAM in UK

First published by the Building Research Establishment (Hereinafter referred to as BRE) in 1990, BREEAM is the oldest method for assessing, rating, and certifying the sustainability of buildings in the world (Awadh, 2017; BREEAM, 2024c). Focused on environmental sustainability and effectively reduced the environmental impact of buildings, this evaluation system adopts the core concept of ‘adapting measures to local conditions and balancing benefits’, making it the only green building evaluation system with both international and local characteristics in the world. More than 2 million buildings worldwide have been registered for

BREEAM certification and over 550,000 of them have been certified by it (NBS, 2024). According to data provided in May 2018, there were a total of 89 BREEAM registered and certified buildings in China, of which 48% were residential buildings, 29% were office buildings, 8% were retail buildings, and 15% were other types of buildings. The registered area was 7,917,188 m^2 and the certified area was 6,528,710 m^2 in China (Wang, 2022).

The BREEAM suite of schemes enables consistent and comparable assessment as well as verification across the entire life cycle of built environment. It comprises six technical standards applicable to the different life cycle stages of a building or project’s, including 'BREEAM In-use', 'BREEAM Refurbishment and fit-out', 'BREEAM Communities', 'BREEAM New construction', 'Home Quality Mark', 'BREEAM Infrastructure' (BREEAM, 2024b). Providing a holistic sustainability assessment framework, BREEAM measures sustainable value across a range of categories and valifies this performance with third-party certification. Each category addresses impact factors, including low impact design and carbon emissions reduction, design durability and resilience, adaption to climate change, and ecological value and biodiversity protection. BREEAM includes twelve categories, such as 'Management', 'Water', 'Energy', 'Transport', 'Health & wellbeing', 'Resources', 'Resilience', 'Land use & ecology', 'Pollution', 'Materials', 'Waste' and 'Innovation'. The BREEAM certification ratings reflect the performance achieved by a project and its stakeholders, as measured against the BREEAM standard and its benchmark. The rating enables comparability between projects and guarantees the performance, quality, and value of the asset (BREEAM, 2024a). The scores of the twelve categories of indicators need to meet the minimum criteria, multiplied by the corresponding environmental weights, and added to the innovation score (BREEAM, 2024c). The BREEAM ratings range from ‘Acceptable’ (for In-Use scheme only) to ‘Pass’, ‘Good’, ‘Very Good’, ‘Excellent’ to ‘Outstanding’. They are reflected in a range of stars on the BREEAM certificate (BREEAM, 2024a).

(2) LEED in US

Developed on the basis of BREEAM, the LEED is currently the most widely implemented and influential green building evaluation standard in the world. Promulgated by the non-profit U.S. Green Building Council (Hereinafter referred to as USGBC) in 1996 (Awadh, 2017), this standard aims to improve the environmental and economic characteristics of buildings, as well as help reduce carbon emissions and improve people's health and well-being. As of 2023, over 105,000 buildings and 205,000 professionals in 185 countries have been certified by LEED

(USGBC, 2024). By the end of 2021, there were a total of 7,712 LEED projects (both certified and in the process of certification) in China, with a total area of more than 360 million m^2, among which were 4,217 certified projects, with a total certified area of more than 140 million m^2. The number of new certification projects increased by 32.53% compared with those in 2020 (Wang, 2022).

LEED assesses the life cycle of a building project, including the process of design, construction, operation, and maintenance of homes, neighborhoods, and buildings. Five versions are included in this evaluation system, namely ‘Green building design and construction (BD+C)’, ‘Green interior design and construction’, ‘Green building operations and maintenance’, ‘Green neighborhood development’, ‘Green home design and construction’. Projects are evaluated with scores up to 100 points in six categories: ‘Sustainable sites’, ‘Water efficiency’, ‘Energy and atmosphere’, ‘Materials and resources’, ‘Indoor environmental quality (Hereinafter referred to as IEQ)’ and ‘Design innovation’. Each category also includes mandatory requirements, which does not receive points. As for the additional points, up to 10 points can be received, among which are 4 points for regional priority credits and 6 points for innovation in design. The evaluation results can be divided into four levels according to the score: Platinum (80 points and above), Gold (60-79 points), Silver (50-59 points), and Certified (40-49 points) (Awadh, 2017; USGBC, 2024).

(3) CASBEE in Japan

CASBEE is a green building certification system developed by a research committee named the Japan Sustainable Building Consortium (Hereinafter referred to as JSBC) (CASBEE, 2024b). A policy called Sustainable Building Reporting System (Hereinafter referred to as SBRS) has been developed by the local governments in Japan, aiming to create a sustainable construction market by the mean of requiring building environmental plans submission to the local building officers. Since the launch of CASBEE for offices in 2002 as the first assessment tool, CASBEE has been adopted by over 24 cities as the standard for their SBRS policies (Wong and Abe, 2014). Due to the relatively short time CASBEE has been operating as a rating system, 606 properties have received CASBEE assessment as of December 2022 (CASBEE, 2023).

Consisting of four evaluation tools called ‘CASBEE for Pre-Design’, ‘CASBEE for New Construction’, ‘CASBEE for Existing Building’, and ‘CASBEE for Renovation’, CASBEE family can accommodate a variety of building types during different stages of construction. It is reflected by the versions include ‘CASBEE for Detached Houses’, ‘CASBEE for Temporary Construction’, ‘Local Government’, ‘CASBEE for Heat Island Effect’, ‘CASBEE for Urban Development’, ‘CASBEE for Market Promotion’, ‘CASBEE for Real Estate’ and ‘CASBEE for Cities’. Four assessment fields have been considered in CASBEE, namely ‘Energy efficiency’, ‘Resource efficiency’, ‘Local environment’, and ‘Indoor environment’. The ranking of buildings is determined by an indicator named the Building Environmental Efficiency (Hereinafter referred to as BEE) in CASBEE. The indicator of BEE is the ratio of Q (Environmental quality) over L (Environmental load), to determine the ranking of S: Excellent, A: Very good, B+: Good, B-: Fairly poor, and C: Poor (CASBEE, 2024a).

(4) DGNB in Germany

DGNB was founded by an independent non-profit association named German Sustainable Building Council (hereinafter referred to as GSBC) in 2007. As a green building evaluation standard, DGNB covers ecological, economic, and social factors, as well as a system of building function and building performance evaluation indicators. DGNB currently has more than 2,300 member organizations, over 10,000 projects in about 30 countries have already been awarded by the DGNB (DGNB, 2023a).

The DGNB system evaluates the overall performance of a certain project from the perspectives of ‘Environmental quality’, ‘Economic quality’, ‘Sociocultural and functional quality’, ‘Technical quality’, ‘Process quality’ and ‘Site quality’ (Ferreira *et al.*, 2023), which can be applied to new buildings, existing buildings, renovations, and buildings in use. Buildings can achieve DGNB certificates in the scale of Platinum, Gold, Silver or Bronze according to the corresponding scores (DGNB, 2023b). DGNB strives to meet building functions and ensure building comfort throughout their whole life cycle, not only achieving environmental protection and low carbon, but also minimizing construction and use costs.

(5) Green Mark in Singapore

Launched in 2005 by Building and Construction Authority (Hereinafter referred to as BCA) in Singapore, the Green Mark certification scheme has been developed to assess the impact and performance of buildings on environment. It provides a comprehensive framework to assess the overall environmental performance of new and existing buildings. As of 2020, more than

4,000 construction projects in Singapore have achieved BCA certification, with a construction area of approximately 123 million m^2, accounting for more than 43% of total construction area in Singapore (Wang, 2022).

The evaluation content consists of 'Climatic responsive design', 'Building energy performance', 'Resources stewardship', 'Smart and healthy building' and 'Advance green efforts' (BCA, 2023). The evaluation results can be divided into three levels according to the score: Platinum (70 points and above), Super Gold (60-70 points), and Gold (50-60 points).

(6) Green building evaluation systems in China

The evaluation of green buildings has been implemented after the promulgation of ESGB-2006. Since then, more targeted evaluation standards have been successively issued for different building types and evaluation fields, such as industrial buildings, hospital buildings, super high-rise buildings, etc. (see Table 2.2). Relevant local regulations, government documents and evaluation standards have been introduced (see Table 2.3), forming a specification system for green buildings in China. With the rapid development of green buildings, MOHURD successively approved the revised version of ASGB-2014 and ASGB-2019, expanding the scope of assessment objects to all kinds of civil buildings and adding operational evaluation indicators. The promulgation of the new standard has become the technical support for green building design, construction, and evaluation in China. Green building design has since become a systematic and comprehensive process, and a large number of design elements need to be comprehensively considered and optimally solved.

Table 2.2 National Green Building Evaluation System in China (1986-2023)

No.	Name of standard	Year of issue	Category of standard
1	Energy-saving Design Standards for Civil Buildings JGJ26-86	1986	Industrial standard
2	Evaluation Standard for Green Building GB/T 50378-2006	2006	National standard
3	Green Energy Saving Management Regulations	2006	-
4	Green Industrial Building Evaluation Guidelines	2010	-
5	Green Construction Evaluation Standards for Construction Projects GB/T 50640-2010	2010	National standard
6	Green Hospital Building Evaluation Standards CSUS/GBC 2-2011	2011	National standard, Association standard
7	Green Shopping Mall Building Evaluation Standards CSUS/GBC 03-2012	2012	National standard, Association standard
8	Technical Rules for Evaluation of Green Super High-rise Buildings	2012	-
9	Green Industrial Building Evaluation Standards GB/T 50878-2013	2013	National standard
10	Green Office Building Evaluation Standards GB/T 50908-2013	2013	National standard

11	Evaluation Standard for Green Campus CSUS/GBC04-2013	2013	National standard, Association standard
12	Urban Lighting Energy Saving Evaluation Standard JGJ/T307-2013	2013	Industrial standard
13	Technical Guidelines for Green Affordable Housing	2013	-
14	Assessment Standard for Green Building GB/T 50378-2014	2014	National standard
15	Green Building Inspection Technical Standard CSUS/GBC 05-2014	2014	National standard, Association standard
16	Implementation Guidelines for Energy Efficient Building Evaluation Standard	2014	-
17	Technical Rules for Green Industrial Building Evaluation	2015	-
18	Green Hospital Building Evaluation Standard GB/T 51153-2015	2015	National standard
19	Green Store Building Evaluation Standard GB/T51100-2015	2015	National standard
20	Technical Rules for Green Building Evaluation Standard	2015	-
21	Green Hotel Building Evaluation Standard GB/T 51165-2016	2016	National standard
22	Technical Code for Operation and Maintenance of Green Building JGJ/T 391-2016	2016	Industrial standard
23	Technical Standard for Prefabricated Timber Buildings GB/T 51233-2016	2017	National standard
24	Technical Standard for Assembled Buildings with Steel-structure GB/T 51232-2016	2017	National standard
25	Technical Standard for Assembled Concrete Structure GB/T 51231-2016	2017	National standard
26	Standard for Assessment of Prefabricated Building GB/T51129-2017	2017	National standard
27	Green Ecological City Evaluation Standard GB/T 51255-2017	2017	National standard
28	Green Building Post-Evaluation Technical Guidelines (Office and Store Building Edition)	2017	-
29	Standard for Green Performance Calculation of Civil Buildings JGJ/T 449-2018	2018	Industrial standard
30	Assessment Standard for Green Building GB/T 50378-2019	2019	National standard, Association standard
31	Building Carbon Emission Calculation Standard GB/T 51366-2019	2019	National standard
32	Technical Standard for Nearly Zero Energy Buildings GB/T 51350-2019	2019	National standard
33	Action Plan for Creating Green Energy-saving Building	2020	-
34	General Specifications for Building Energy Conservation and Renewable Energy Utilization GB 55015-2021	2021	National standard
35	Evaluation Standard for Green Renovation of Existing Building GB/T 51141-2021	2021	National standard
36	Green Building Label Management Measures	2021	-
37	Evaluation Standard for Green Construction of Building and Municipal Engineering GB/T 50640-2023	2023	National standard

Table 2.3 Local Green Building Evaluation Systems in China (2008-2023)

No.	Region	Name of standard	Year of issue
1	Zhejiang Province	Green Building Evaluation Standard of Zhejiang Province DB33/T1039-2007	2008
2	Guangxi Province	Green Building Evaluation Standard of Guangxi Zhuang Autonomous Region DB45/T 567-2009	2009
3	Jiangsu Province	Green Building Evaluation Standard of Jiangsu Province	2009
4	Shenzhen City	Green Building Evaluation Regulation of Shenzhen City SZJG30-2009	2009
5	Hubei Province	Green Building Evaluation Standard of Hubei Province (Trial)	2010
6	Hong Kong	Green Building Evaluation Standard (Hong Kong Version) CSUS/GBC1-2010	2010
7	Shaanxi Province	Green Building Evaluation Standard Implementation Rules of Shaanxi Province (Trial)	2010
8	Hainan Province	Green Building Evaluation Standard of Hainan Province DBJ46-024-2012	2012
9	Shanghai City	Green Building Evaluation Standard of Shanghai City DG/TJ08-2090-2012	2012
10	Liaoning Province	Green Building Evaluation Standard of Liaoning Province DB21/T2017-2012	2012
11	Sichuan Province	Green Building Evaluation Standard of Sichuan Province DBJ51/T009-2012	2012
12	Yunnan Province	Green Building Evaluation Standard of Yunnan Province DBJ53/T-49-2013	2013
13	Gansu Province	Green Building Evaluation Standard of Gansu Province DB62/T25-3064-2013	2013
14	Ningxia district	Green Building Evaluation Standard of Ningxia Hui Autonomous Region DB64/T954-2014	2014
15	Neimenggu district	Green Building Evaluation Standard of Neimenggu Autonomous Region DBJ03-61-2014	2014
16	Chongqing City	Green Building Evaluation Standard of Chongqing City DBJ/T50-066-2014	2014
17	Fujian Province	Green Building Evaluation Standard of Fujian Province DBJ/T13-118-2014	2014
18	Hunan Province	Green Building Evaluation Standard of Hunan Province DBJ43/T314-2015	2015
19	Henan Province	Green Building Evaluation Standard of Henan Province DBJ41/T109-2015	2015
20	Qinghai Province	Green Building Evaluation Standard of Qinghai Province DB63/T1110-2015	2015
21	Jilin Province	Green Building Evaluation Standard of Jilin Province DB22/JT137-2015	2015
22	Heilongjiang Province	Green Building Evaluation Standard of Heilongjiang Province DB23/T1642-2015	2015
23	Jiangxi Province	Green Building Evaluation Standard of Jiangxi Province DBJ/T36-029-2016	2016
24	Tianjin City	Green Building Evaluation Standard of Tianjin City DB/T29-204-2015	2016
25	Hebei Province	Green Building Evaluation Standard of Hebei Province DB13(J)/T113-2015	2016
26	Beijing City	Green Building Evaluation Standard of Beijing City DB11/T825-2015	2016
27	Guangdong Province	Green Building Evaluation Standard of Guangdong Province DBJ/T 15-83-2017	2017
28	Shandong Province	Green Building Evaluation Standard of Shandong Province DB37/T5097-2017	2017

29	Shanxi Province	Green Building Evaluation Standard of Shanxi Province DBJ04/T335-2017	2017
30	Guizhou Province	Green Building Evaluation Standard of Guizhou Province DBJ52/T065-2017	2018
31	Xinjiang district	Green Building Evaluation Standard of Xinjiang Autonomous Region XJJ 126-2020	2020
32	Xizang district	Green Building Evaluation Standard of Xizang Autonomous Region DB54/T 0276-2023	2023

(i) ESGB-2006 (Evaluation Standard for Green Building GB/T 50378-2006)

According to the requirements of MOHURD, the first Chinese national evaluation standard ESGB-2006 was compiled by a range of government agencies in 2006, such as China Academy of Building Research (Hereinafter referred to as CABR) and Shanghai Research Institute of Building Sciences (Hereinafter referred to as SRIBS). The definition, evaluation indicators and methods of green buildings have been firstly clarified in this specific standard, laying an important foundation for assessing the greenness of buildings, ensuring the quality of green buildings, and guiding the healthy development of green buildings in China. It takes building groups and building units as the evaluation objects, which has been applied to residential buildings and public buildings (e.g., office buildings, shopping malls and hotel buildings).

(ii) ASGB-2014 (Assessment Standard for Green Building GB/T 50378-2014)

On the basis of ESGB-2006, MOHURD made a revision of green building evaluation standard and issued ASGB-2014 in 2014. This standard divides the evaluation of green buildings into design and operation stage, with a single building or building group as the evaluation object. The evaluation scope has extended from residential buildings and public buildings to all kinds of civil buildings, forming a technical standard system covering the whole process of green building design, construction, review, evaluation, operation and maintenance and testing.

(iii) ASGB-2019 (Assessment Standard for Green Building GB/T 50378-2019)

Based on the version of ASGB-2014, MOHURD promulgated the second revision of ASGB-2019 in 2019. This new standard makes new requirements for construction projects when applying for green financial services, requiring such projects to form a special report containing energy-saving measures, water-saving measures, building energy consumption and carbon emissions. By the end of 2020, the cumulative green construction area in China reached 6.645 billion m^2. In 2020, new green buildings accounted for 77% of new civil buildings in towns. A recent statistic indicated that the total number of projects with green building labels in China has reached 24,700, with a construction area of more than 2.569 billion m^2 (Wang, 2022).

As for the Chinese green building evaluation system, scholars generally conduct comparative studies on green building evaluation standards between China and other countries (Shi and Xu, 2007). Yang (2008) investigated the development history, assessment methods, assessment criteria, weighting, and rating system of the five green building evaluation systems, namely BREEAM, LEED, GB Tool, CASBEE and ESGB-2006. The improvement measures and development opportunities of Chinese green building evaluation system have been highlighted. (Zhang, 2011) conducted a comparative study on the development history, assessment objects, assessment contents and assessment mechanisms of LEED, BREEAM, CASBEE, GBTOOL and ESGB-2006. Case study has been carried out for each evaluation standards to illustrate their corresponding characteristics. On this basis, theoretical suggestions for the improvement of Chinese evaluation system have been put forward. (Lin, 2017) conducted a comparative study on ESGB-2006 and LEED. The general comparative contents included national policies, member construction, assessment objects, scoring methods, assessment criteria categories, weighting systems, etc. An evaluation standard optimization model has been constructed by using analytic hierarchy process (Hereinafter referred to as AHP) and expert questionnaire survey method to determine the weight of the evaluation indicators. A case study has been used to verify the feasibility of the evaluation model. Guo et al. (2019) conducted a comparative study on the policy development, indicator content, evaluation methods and grade classification between EEWH-BC in Taiwan and ASGB-2014. Suggestions to promote the development of green buildings have been proposed from the aspects of corporate sustainable development concepts, green construction, green technology, and policy legislation. Yu et al. (2019) conducted a comparative study between ASGB-2014 and BREEAM-NC regarding a couple of criteria such as energy efficiency, water and material saving, site and environment. Further discussions aimed at criteria covering range, assessment contents, weighting system determination.

2.1.4. Energy consumption simulation software

The heat gain and loss of a building is a dynamic process that changes with the outdoor environment and time. Due to the inaccuracy of the steady-state calculation, dynamic calculation methods such as the heat balance method, weighted coefficient method, and harmonic response method will be needed. The commonly used international dynamic energy consumption simulation software are DOE-2, EnergyPlus, DesignBuilder, DeST, and TRNSYS, etc., while BESI is a main regional simulation software that has been currently used in Chinese construction industry.

(1) DOE-2

Developed by James J. Hirsch & Associates in collaboration with the Lawrence Beckley National Laboratory in the US, DOE-2 is a widely used building energy analysis program that can predict energy use and costs for all types of buildings. DOE-2 simulates the building on an hourly basis and estimates utility costs using a user-supplied description of the building layout, structure, operating schedules, air conditioning systems (lighting, HVAC, etc.), and utility rates, along with weather data (James, 2025). There are four calculation modules in DOE-2: computer room, air system, load calculation, and economic analysis. The main function of the computer room module is to calculate and analyse the energy consumption of the building. The air system module is mainly to calculate and analyse the cooling or heating required by the system to maintain a certain temperature. The load module is to calculate the cooling and heating loads based on local meteorological data and the building model's information. The economic module is mainly used to analyse the full life cycle of building, including the cost of building and system equipment, maintenance costs, and interest rates, etc. At present, DOE-2 software is a widely used building energy consumption simulation and analysis software. According to statistics, more than 40 countries and regions around the world have adopted DOE-2 software when formulating building energy-saving standards and building designs (Yang, 2020).

(2) EnergyPlus

Jointly developed by the University of Illinois and Lawrence Berkeley National Laboratory based on BLAST and DOE-2 energy consumption simulation software, EnergyPlus is a whole-building energy simulation program used by engineers, architects, and researchers to simulate a building's energy consumption (heating, cooling, ventilation, lighting, plug and process loads) and water usage (EnergyPlus, 2025). EnergyPlus adopts a synchronous simulation calculation method that integrates systems, equipment, and loads. This software can automatically adjust or manually set the time step for simulation calculation. The heat transfer and load calculation of the building envelope structure adopt the reaction coefficient method and the heat balance method respectively. Being used to calculate the solar radiation heat gain of glass and the heat transfer of external windows, EnergyPlus can simulate and analyse the thermal performance of windows. The thermal comfort calculation of the building adopts a thermal comfort model established based on data such as population activity, indoor humidity, and indoor temperature. In addition, users can add other functional modules such as natural lighting simulation and lighting energy consumption simulation according to their requirements. Although it is a widely used building energy consumption simulation and analysis software, certain limitations such as a lack of an intuitive and easy-to-operate user interface exist in EnergyPlus.

(3) DesignBuilder

Developed by the British DesignBuilder company, DesignBuilder has the most advanced performance analysis tools and an easy-to-use interface. It is an integrated set of in-depth, high-productivity tools to assist with sustainable building design and assessment. With a clear and well-structured layout and an intuitive help system, this software can create professional geometry much easier than with other simulation packages. The ease of use also extends to other areas of the program, such as thermal bridge analysis and HVAC system setup, with the ability to easily simulate adjacent ground conditions (DesignBuilder, 2025). It can quickly establish and analyse building models and is widely used by architects, engineers, energy consulting companies, etc. The energy consumption simulation of this software is optimized based on the internationally recognized building energy consumption simulation program EnergyPlus, integrating the advantages of EnergyPlus and making up for the shortcomings of its operating interface. Through the pre-set data modules, parameters such as building structure, internal human activities, HVAC, and lighting systems can be loaded, thus simulating the temperature, lighting, ventilation, comfort environments of the building model. The output results can be presented in a variety of forms, which is convenient for data analysis and suitable for any stage of building design.

(4) DeST

DeST is a building environment and HVAC system simulation software developed by Tsinghua University for building energy consumption simulation analysis and building environment equipment system optimization design. Equipped with building analysis and annual hourly meteorological data analysis modules, the meteorological data of more than 100 cities in China are included in DeST, which can simulate the indoor cooling load of buildings hourly. At the same time, a building shadow calculation module and a natural ventilation simulation module are integrated in this software. The impact of meteorological conditions such as solar radiation and natural ventilation will be considered when conducting building energy consumption simulation (Yang, 2020).

(5) TRNSYS

TRNSYS is an energy consumption simulation software developed by the Solar Energy Research and Development Laboratory of the University of Wisconsin, USA. TRNSYS is an extremely flexible graphical software environment for simulating the behaviour of transient systems. While most simulations focus on evaluating the performance of thermal and electrical systems, TRNSYS is equally applicable to simulating other dynamic systems such as traffic flow or biological processes (TRNSYS, 2025). By using the modular analysis method, TRNSYS requires users to use relevant modules to set up building models. Compared with other energy consumption simulation software, TRNSYS has obvious advantages in the optimization design of systems or equipment. However, this software is relatively simple in model setting, which makes it obviously insufficient in calculating the thermal performance of the envelope structure. Meanwhile, the shadow and ventilation of buildings cannot be simulated in TRNSYS, which will need the support of other simulation software.

(6) BESI

GBSWARE is a commonly used building simulation technology platform in Chinese local construction industry. Based on the BIM framework, building environment can be simulated from aspects such as energy-saving design (BECS), energy consumption calculation (BESI), HVAC load analysis (BECH), building ventilation analysis (VENT), sunlight analysis (SUN), residential thermal environment analysis (TERA), indoor thermal comfort analysis (ITES), lighting analysis (DALI), building acoustic environment analysis (SEDU) and carbon emission analysis (CEEB) (Chen et al., 2020). This provided technical support and provision docking for green building evaluation in China. Based on the DOE-2 core, BESI can be seamlessly connected with the building energy-saving model, accurately obtain the dynamic ideal load, calculate the energy-saving rate and the total building energy consumption required by the 'Standard for Building Energy Performance Certification JGJ/T 288-2012' (Hereinafter referred to as SBEPC-2012) and ASGB-2019 (GBSWARE, 2024c). This specific software supports the energy consumption calculation of common HVAC equipment, the setting functions of heating and cooling periods, system division and operation strategy, etc. The disadvantage is that GBSWARE only has a Chinese version, which means that the analysis process and results of simulation calculation need to be translated into English. The comparison of performance among the above software is given in Table 2.4.

Table 2.4 Performance comparison of energy consumption simulation software

Software	DOE-2	EnergyPlus	DesignBuilder	DeST	TRNSYS	BESI
Graphical interface	√	x	√	√	√	√
Dynamic simulation	Hourly	Minutely	Minutely	Hourly	Hourly	Hourly
Sky radiation	√	√	√	x	√	√
Shading	√	√	√	√	√	√
Natural ventilation	x	√	√	√	√	x
Lighting	√	√	√	√	√	x
Precise temperature calculation	x	√	√	√	√	√
Thermal comfort	x	√	√	x	x	x
Economic evaluation	x	x	x	√	√	x
Customized report output	x	√	√	x	√	√

(Source: Yang, 2020.)

2.2. External shading design assessment

The design of building external shading is closely related to the local geographical environment and climatic conditions. The heat of solar radiation mainly enters the room in two ways. One is the daylighting opening of the building's external envelope structure, such as skylights, side windows and atrium glass roof. The other is the non-daylighting opening of the building's external envelope structure, such as walls, roofs, etc.

2.2.1. The category of external shading design

There are many kinds of shading components, and the shading design of different parts is also targeted. For the side window part, apart from the flat shading panels (wood, cloth curtains, blinds, etc.), the way to achieve shading using artificial components has been divided into three types based on their characteristics and categories: horizontal shading, vertical shading, and grille shading. For roof skylights and glass roofs, cloth curtains and grilles can give full play to the shading effect. In addition to shading components, the use of natural sources such as greening and vegetation also have a very ideal shading effect (Liu, 2002). Building window shading can also be divided into external shading and internal shading. Compared with internal shading, the external shading components can not only block a large amount of solar radiation from entering the room, but also reduce the area of heat absorption by the glass, indicating that the external shading design can play a better role in improving the indoor thermal environment. The principle of non-window external shading is similar to that of window external shading, except that the affected object is replaced by the wall or roof instead of the glass. Therefore, the basic principle of building window external shading is to reduce the transmittance of glass receiving solar radiation, to better control sunlight entering the room, while reducing the heat absorbed by the external enclosure structure, thereby improving the indoor thermal environment comfort (Yang, 2019).

2.2.2. Classification of external shading products in Chinese market

Lin *et al*. (2020) investigated the main shading measures and existing shading products in Chinese market (see Figure 2.1). Various classification methods have been applied in building shading. Different shading categories can derive a variety of shading products. The shading measures can be divided as follow:

(1) Permanent shading, seasonal shading, and temporary shading based on the usage time of shading facilities.
(2) Rigid shading and flexible shading based on the material characteristics of shading products.
(3) Adjustable shading and fixed shading based on the mobility of shading system.
(4) Natural shading and artificial shading based on the main body of shading facilities.
(5) Internal shading, self-shading, external shading, and hollow shading based on the installation position of shading facilities.
(6) Horizontal shading, vertical shading, integrated shading, and baffle-type shading based on the layout of shading facilities.

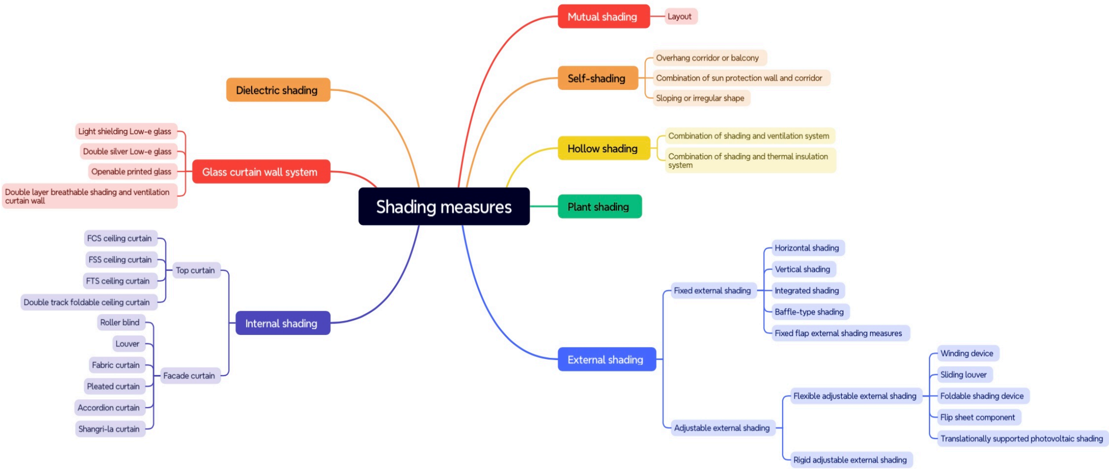


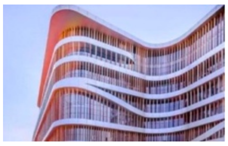
Figure 2.1 Main shading measures and existing shading products in Chinese market

(Source: Lin *et al*., 2020.)

1.2.3. Materials of external shading devices

The common external shading materials and their characteristics have been investigated by some Chinese scholars (Wang, 2015; Zhong, 2021; Wang, 2022), such as concrete panel, fabric, and wood. With the development of production technology, there is a wide variety of existing shading materials can be chosen (see Table 2.5), such as metal, plastic, fibreglass, coated film, special glass, clay panel and photovoltaic panel. Material characteristics are summarized in Table 2.5.

Table 2.5 Characteristics of external shading materials

Materials	Characteristics	Sample
Concrete panel	Commonly used for fixed external shading structures, have good performance of durability, safety, strong wind resistance, anti-static effect, and low cost.	
Fabric	Commonly used for shading tarpaulins and shading curtains, soft texture, and various colors, have good performance of weather resistance and tensile strength.	
Wood	It is light in texture and easy to process. The performance of weather resistance and corrosion resistance is not as good as metal. It needs to be sterilized, stored, dried and surface treated later.	

Metal	Aluminum alloy materials have low density, high strength, and good corrosion resistance, with high value of recycling value and energy-saving.	
	The self-supporting structure of stainless steel is corrosion-resistant and easily adaptable to outdoor, coastal, hot, and humid climates. The structural size is greatly reduced compared with aluminum materials.	
Plastic	Low cost and easy to shape, has a shorter service life than metal.	
Fibreglass	Commonly used in sunshade curtains, anti-UV fabrics, etc., has good performance of resistant to aging, air permeability, shading and heat insulation, without affecting indoor brightness.	
Coated film	Glass films and coatings can insulate, retain heat, and have a high ignition point. Film-coated glass has single-phase reflective and anti-corrosion functions, but curling may occur later and cannot be repaired, they can only be re-filmed.	
Special glass	Commonly used in high-end office buildings, libraries, museums, etc., to selectively pass and absorb light.	
Clay panel	Easy to clean, rich in color, protects building walls from bad weather and air pollution. Cavity structure, light weight, Have good performance of heat preservation and insulation.	
Photovoltaic panel	Solar panel integrates solar energy with sunshade and adjusts according to the sun angle. It can fully generate electricity when the shading effect is good. However, the cost is high, failure is prone to occur, and subsequent maintenance is complicated.	

(Source: Wang, 2015; Zhong, 2021; Wang, 2022.)

2.2.4. The importance of external shading design

Effectively preventing the solar radiation from entering the room through glass windows, the external shading facilities are the most economical and effective way of passive energy-saving measures. An important measure to prevent solar radiation from entering the room is the design of window external shading. To understand the basic principles of building window external shading, the effects of solar radiation on building windows should be clarified. Solar radiation directly hits the glass window, which mainly produces three kinds of impact, namely reflected light, transmitted light, and glass heat absorption. Reflected light will not enter the room, so the indoor thermal environment is not able to be affected. Transmitted light will enter the room, thereby increasing the indoor air temperature. Glass heat absorption will cause the glass surface temperature to rise, dissipate heat to the room, and indirectly affect the indoor air temperature. If the window is close to the glass, it is difficult to completely block solar radiation. Thus, it is very necessary to set up shading measures at the window (Yang, 2019), especially the external shading design.

2.2.5. Assessment of external shading design

As mentioned in the Introduction part, Bellia *et al*. (2014) divided the solar shading devices into three categories, e.g., fixed shading, adjustable shading, and other shading types. Scholars normally applied a variety of simulation software to assess the energy-saving impact of shading devices on buildings, whilst other building performance can also be analysed at the same time, such as lighting, ventilation, indoor thermal comfort, etc. In addition, carbon emissions analysis of the shading facilities has been conducted along with their energy efficiency effects in a small number of studies (Huang *et al.* 2012). Relevant literature will be reviewed from energy-saving, economic and environmental perspective.

(1) Energy-saving impact

(i) Type of external shading devices

1) Fixed shading devices

As for the fixed shading devices, Liu (2010) carried out energy consumption simulation of fixed horizontal wing-shaped sunshades for a public building by DeST. The impact of different building orientations and various widths of sunshade on building energy efficiency has been analysed. Liu (2011) used Ecotect, Phoenics, Daysim and DeST to explore the impact of the protrusion coefficient regarding the horizontal and vertical shading components on luminous flux, illumination ratio, ventilation volume, lighting energy consumption and air conditioning energy consumption for residential buildings in Guangzhou city. Park *et al.* (2020) analysed the energy performance and thermal comfort for a retrofitted educational building with a shading system applying Phase Change Materials (Hereinafter referred to as PCMs) in South

Korea. Results showed that the cooling energy consumption decreased by 44% and the number of thermal comfort hour improved by 34% after adopting PCMs. Zhou *et al.* (2022) adopted Honeybee and scSTREAM to simulate the performance of indoor lighting, energy consumption, thermal comfort, and wind environment of an office building in Nanjing. A comprehensive performance evaluation model of external shading components has been developed by using AHP and scoring method.

2) Adjustable shading devices

For the adjustable shading devices, Yang (2020) believed that the energy-saving effect of adjustable external shading can achieve 3.89%-10.24% higher than that of the fixed strategies under the same number of horizontal plate layers. Li *et al.* (2012) explored the cooling load and the required luminous flux under the conditions of unshaded, venetian blinds with 45° and 90° opening angles by using eQuest and EnergyPlus. The best periods for their specific opening angle have been analysed. Singh *et al*. (2016) performed the uncertainty and sensitivity analysis to prioritize the most influencing parameters for glazed components design with external venetian blind for office buildings in hot-dry climate of Jodhpur. EnergyPlus, Hyper Cubic Sampling and extended FAST methods have been adopted. The window to wall ratio, glazing type, blind type and slat angle were regarded as the highly influencing parameters for energy and visual performance by sensitivity analysis. Moreover, a large uncertainty in lighting, Heating Ventilation and Air Conditioning (Hereinafter referred to as HVAC), source energy consumptions, and Useful Daylight Illuminance (Hereinafter referred to as UDI) has been identified. Tabadkani *et al*. (2021) adopted Energy Management System and Ladybug to assess the adaptable venetian blinds on energy performance and occupant thermal/visual comfort in nine cities located in different climate zones. Five shading control strategies with 38 activation thresholds of the automated venetian blinds were tested for the potential impacts on energy savings and indoor comfort.

3) Other types shading devices

For the other types shading devices, Xu (2010) established a model based on a residential building in Changsha city in Energyplus. The comparative analysis results showed that the highest energy-saving rate for cooling energy in summer was the shading mode three, a combination strategy of roof, wall, and the integrated external shading. This shading mode achieved energy-saving effect of up to 17.88% in summer, but the corresponding annual energy-saving rate was less than 4%. The adjustable external shading design for residential buildings in this specific climate region was recommended, with the characteristic of ‘open in summer and closed in winter’. Li *et al.* (2011) established two models of public building and residential building based on DOE-2 to explore the energy-saving effects of the fixed and adjustable shading facilities in Ningbo city. The energy-saving rate of residential building and public building with adjustable external roller shading increased from 50% to 53.6% and 53%, respectively, better than those with the fixed shading board which increased to 53.1% and 52.6%. Zhang (2016) used Design builder to analyse the impact of fixed louver external shading devices on the total energy consumption and thermal comfort of public buildings in Tianjin. These studied shading measures varied from different forms, sizes, and inclination angles. The simulation analysis results showed that the west-facing façade has greater energy-saving potential. Under the manual control system, the energy-saving rate of the fixed horizontal external shading louvers reached 8%-13%, whilst the vertical external shading louvers reached 2%-8%. Under the intelligent control system, the energy-saving rate of the horizontal external shading louvers reached 14.8%, whilst the vertical external shading reached 11.4%. Sun *et al.* (2018) analysed the energy-saving, lighting and ventilation performance for a comprehensive teaching and laboratory building with external shading devices in the cold climate city of Jinan. The horizontal shading components, adjustable horizontal shading components, horizontal shutter shading and vertical shutter shading were included. Jiang (2021) investigated the annual energy consumption of lighting, heating, and cooling for the fixed louver shading devices under 15 shading angles by Energyplus. Simulation results showed that the orientation with the most significant impact on building energy conservation under the optimal fixed shading angle was east and west in this specific case. Compared with the fixed shading method, the dynamic shading method can achieve the most significant energy-saving effect in the south and north-facing rooms, and can significantly improve the indoor light environment, stabilize the thermal environment, and reduce overall energy consumption.

(ii) GBSWARE software usage

Considering the practicality and common usability of simulation software on GBSWARE technical platform in the Chinese construction industry (e.g., various architectural design institutes, green building consulting agencies and green building evaluation institutes, etc), some Chinese scholars carried out relevant research by using the software on GBSWARE (see Table 2.6). As for the external shading design, Lu (2011) established an energy-saving building model by using BECS, to compare the power consumption of cooling system regarding different forms of reinforced concrete fixed external shading components and glass made fixed louver shading devices for a residential building in Guangzhou. The optimum shading scheme included horizontal sunshades set in the east-facing and partial west-facing facade, the integrated sunshades set in the west-facing and partial south-facing façade, and the fixed glass louver sunshades set in the east-facing and partial west-facing facade. It can be estimated that the annual power consumption saving of the optimum shading strategy reached 20.15%, and the corresponding annual power expenditure saving was about ¥1654.32 (equivalent to GBP 179). The author further pointed out that the cost of making this optimum shading design was about 2% of the total cost of the building, of which investment can be recouped in 2-3 years after the building has been put into use. Yang (2019) conducted simulation study on the energy-saving and lighting effects of 24 fixed external shading designs for an office building in Nanchang area, by using software of BESI 2018 and DALI 2018. Simulation results showed that the optimal shading form with the best comprehensive shading effect for the south-facing window was horizontal louver shading, with overhang length less than 150mm and the louver spacing between 600mm and 800mm. As for the west-facing window, the horizontal louver shading had the best comprehensive shading effect, with overhang length less than 150mm and the louver spacing between 600mm and 800mm. The optimal shading option for the east-facing window was the vertical louver shading, with overhang length between 150mm-250mm and louver spacing between 600mm-800mm. Zhong (2021) constructed a building model based on an educational building in Chengdu, to investigate the energy-saving and lighting impact of the various fixed external shading strategies by using BESI 2020 and DALI 2020. The respective optimum shading type and shading dimension for each building façade can be determined. As for the south-facing façade, the horizontal shading alternative achieved 1.01% energy-saving rate, with the dimension of 384mm width and 720mm long. As for the east-facing façade, an 8-layers of vertical shading alternative with an inclination angle of 40º achieved 3.58% energy-saving rate, with overhang length of 426mm and a spacing of 675mm. As for the west-facing façade, a 5-layers horizontal shading strategy achieved 2.66% energy-saving rate, with overhang length of 394mm and a spacing of 480mm. Zhang (2022) established three types of classroom models based on the educational buildings in Zhuzhou. The energy-saving and lighting effects of various fixed external shading strategies for the three models have been analysed by using BESI 2020 and DALI 2020. The studied shading design included horizontal, vertical, integrated, baffle-type, horizontal louver, and vertical louver shading.

Table 2.6 Literature in the field of construction by using simulation software on GBSWARE platform

No	Author	Literature	Research content	Building type	Software
1	Lu (2011)	Building energy saving analysis of shading measures	Study on the power consumption of cooling systems regarding various fixed external shading strategies and analyse the power expenditure saving for an optimum shading alternative.	Residential building	BECS
2	Shen (2019)	Research on Kunming area kindergarten activity unit natural lighting optimization	Study on the lighting effect and energy consumption impact of different design strategies regarding different orientations, window to wall ratios, glass materials, external shading types, etc., to provide the optimization natural lighting suggestions.	Educational building	Ecotect, Radiance, BECS
3	Yang (2019)	The research on design technology of fixed outer shading for office building window in Nanchang Area	Study on the shading effect of the fixed external shading strategies to determine the optimum shading design with the best comprehensive benefit for each building façade.	Public building	BESI 2018, DALI 2018
4	Chen *et al.* (2020)	Study on the energy-saving rate of air conditioning system in public buildings - taking a public building in Tanghai County as an example	Design three renovation strategies of cooling system to determine the optimum option with the highest energy-saving rate.	Public building	BECS
5	Jiang (2020)	Study on the evaluation method of building external sunshade based on building comprehensive performance analysis-taking	Construct a comprehensive assessment method for the fixed external shading components from the perspectives of indoor lighting environment, indoor ventilation environment, indoor thermal environment, energy	Office building	Grasshopper, scSTREAM, DALI

		Nanjing office building as an example	consumption and visibility of sight.		
6	Zhong (2021)	Study on shading design of teaching building outside window in Chengdu area	Analyze the lighting effect and energy conservation performance of the fixed external shading strategies to determine the best shading type and dimension for each building façade.	Educational building	Ecotect, BESI 2020, DALI 2020
7	Zhang (2022)	Study on the optimization of external shading of teaching building in college station vocational education of Zhuzhou	Analyze the energy consumption and indoor lighting effect of various types of fixed external shading design and propose the key points of corresponding optimal shading design.	Educational building	BESI 2020, DALI 2020
8	Cao (2023)	Study on natural lighting in the reading space of Xuzhou University library based on light comfort	Analyze the impact of optimization design measures regarding the building orientation, bay size, floor height, window size, glass material, external shading design, light guide installation, and reflector setting on the indoor light environment.	Educational building	DALI 2023

(2) Economic impact

Various factors involved in the design process of buildings, especially public buildings, require occupants and designers to go beyond the thermal performance of the building design, but to repeatedly compare the attributes of each design option, such as investment costs. This is to make optimal design decisions. As one of the elements of modern value engineering (Lu *et al.*, 2016), LCC has great research and practical value in the process of architectural design. Belongs to a traditional Life Cycle Thinking (Hereinafter referred to as LCT) technique, the Life Cycle Assessment (Hereinafter referred to as LCA) approach is considered to be a useful tool for assessing the impact of relevant activities throughout the lifecycle of a project. Defined by ISO 14040:2006, LCA is a method to quantify and assess the energy and environmental costs and potential impacts of a product, an activity, or a management process throughout its lifecycle (Fregonara, 2017). As another category of LCT technique, LCC represents the life cycle analysis of products or services from a purely economic perspective, defining by ISO 15686-5:2008. The LCC approach has been used to compare various retrofit interventions for buildings to determine the optimal level of cost from a financial and energy perspective (Pinto *et al*., 2023). Traditionally speaking, higher initial investment costs are required when considering the adoption of advanced green technologies for buildings, whilst this is one of the primary reasons why energy-efficient buildings are difficult to gain popularity in the construction market (Ryghaug and Sørensen, 2009). However, the durability of building construction and its long-term investments or returns have been overlooked. When selecting a certain building component, decision-makers, and stakeholders in the construction industry concern more about its initial expenses and budget (Marszal and Heiselberg, 2011). In the long run, when selecting some kinds of building designs and components, decision-makers should pay more attention to their LCC. In the construction sector, LCCA can be used to compare design alternatives for any building or system, considering the costs and savings of each alternative over its entire life cycle. This analytical approach can be applied at a variety of investment-related decision levels to assess the economic value of various designs, projects, alternatives, or system investment strategies to obtain the best return (Walls, 1998).

However, there are currently only a few studies on the assessment of shading designs from an economic perspective by using LCCA method. Jaber and Ajib (2011) investigated the technical, energetic, and economic optimization of different passive measures in a typical Jordanian residential building in the Mediterranean region. This included the best orientation of building, window size, thermal insulation thickness, shading devices, etc. The authors adopted TRNSYS software to estimate the heating and cooling energy demand, thus determined the optimum window size from the total façade area. Simulation results showed that shading devices installed on the south façade could effectively avoid solar radiation entering the building and lead to the lowest annual cooling energy demand, compared to other window size alternatives. The south façade with shading devices was then proved to be more economic through LCC method. It can be noted that LCC was useful for identifying solutions that could guarantee thermal comfort for occupants at the lowest cost, and the consideration of applying energy-saving measures at the early design stage was important to achieve this goal. Apart from using LCC approach for an individual analysis, some scholars preferred to combine LCC and LCA methods for an integration analysis regarding the environmental and economic performance of solar shading equipment. Babaizadeh *et al.* (2015) applied LCA to compare the effects of three specific shading materials (Wood, Aluminum, PVC) on building energy consumption and environment. Meanwhile, the economic performance of the shading products was assessed by LCC method, considering their first and future costs. This study was carried out in residential buildings located in the five climate zones in the US, such as hot-humid (Miami), mixed-humid (Atlanta), marine (Seattle), cold (Chicago), very cold (Duluth). The authors adopted the Building for Environmental and Economic Sustainability model and SimaPro 8.0 software to develop the Life Cycle Inventory (Hereinafter referred to as LCI) of the external shading systems throughout their life cycle stages. This included manufacturing process, in-service, and end of life, emphasizing their environmental loads despite the positive impact on fossil fuel depletion. The results of economic-environmental performance suggested that a wood shading unit was the best alternative.

In spite of the numerous advantages on the adoption of LCCA when making decisions, it has not yet been considered by decision-makers and developers in the construction industry. The reasons for this are largely due to the lack of understanding on the actual energy-saving performance of green strategies, the lack of reliable data, and the uncertainty of their potential future savings, etc. (Morrissey and Horne, 2011; Dwaikat and Ali, 2018). In addition, the adoption of LCCA in the green building industry, especially for the external shading measures, is relatively low. A small number of studies have applied this analysis method, such as vertical green shading in tropical areas (Huang *et al*., 2019; Huang *et al*., 2021). Since the information asymmetry and insufficient cooperation between relevant stakeholders, (e.g., architectural design institutes, building developers and external shading manufacturers), has prevented the growth of LCCA on external shading measures. Therefore, there is a need to extend this analysis method on the economic impact assessment of external shading devices.

(3) Environment impact

As mentioned above, to investigate the environmental impact on the building materials and products, LCA is a great technique that can be used to assist the decision-makers for choosing more sustainable solutions (Babaizadeh *et al*., 2015). Nevertheless, there are currently limited number of studies using LCA to assess the environmental effects of the external shading facilities. In addition, the other two mainstream methods to assess the environmental impacts of building construction is Life cycle energy assessment (Hereinafter referred to as LCEA) and $LCCO_2A$ (Chau *et al*., 2015). One of the keys to achieving low-carbon design of building structures is the scientific assessment of their carbon emissions throughout building life cycle.

Xu *et al.* (2023) introduced three main methods for $LCCO_2$ calculation, such as process-based method (Li *et al*., 2016; Roh and Tae, 2017; Wu *et al*., 2017), input-output analysis method (Guo *et al*., 2012; Tian *et al*., 2013), and hybrid methods (Crawford, 2014; Dixit *et al*., 2015). The process-based method divides the building life cycle into multiple production processes. Carbon emissions can be calculated based on process activity data and carbon emission factors (Roh and Tae, 2017). The 'Standard for Building Carbon Emission Calculation' GB/T 51366-2019 (Hereinafter referred to as SBCEC-2019) promulgated by Chinese government in 2019 is based on the process-based method (MOHURD, 2019c). The process decomposition and calculation workload are heavy although the process-based method is simple and can provide carbon emissions in detail at each life cycle stage. In addition, the incomplete life cycle boundaries exist due to the overlook of certain minor processes, bringing truncation errors to the calculation (Lenzen, 2000; Nässén *et al*., 2007). In order to avoid the truncation errors in the process-based method, it is recommended to use input-output analysis. A carbon emission coefficient matrix has been constructed by input-output analysis, to the value-based economic input-output table. This can convert monetary values into carbon emissions and calculate carbon emissions in the entire building industry (Onat *et al*., 2014; Zhang and Wang, 2017). The inaccurate calculations of carbon emissions for a single building existed if only considering the average emission factors in this method (Zhang and Wang, 2016a). Combining the advantages of process-based methods and input-output analysis, hybrid methods have become increasingly popular (Zhang and Wang, 2016b; Zhang *et al*., 2020). In addition to allow the use of a more complete life cycle boundary at the macro level, this hybrid approach can maintain the accuracy of carbon emission calculations for a single building.

As a relatively cutting-edge research concept, $LCCO_2A$ takes into account all carbon equivalent emissions at different stages of a building's life cycle. There are only a few studies on $LCCO_2A$ for buildings. Based on BIM technology and life cycle assessment technology, Gao (2016) used Design builder to calculate the annual energy consumption and $LCCO_2$ emissions of an office building in Taiyuan. The author divided the building life cycle into four main stages: planning and design, materialization, operation, demolition, and disposal. The carbon emissions in the materialization and operation stages were calculated through software simulation, and the carbon emissions in the demolition and disposal stages were estimated at 90% of the energy consumption in the construction stage. Based on the simulation calculation results of building carbon emissions, the general methods of low-carbon design of green buildings and emission reduction measures in the materialization and use stages were proposed.

Based on the scope of carbon emission calculation and inventory analysis, Yang (2017) established a carbon emission calculation model for the whole life cycle of a building. In this research, the whole life cycle of a building has been divided into five stages: building material production, building material transportation, construction and installation, O&M, and demolition and disposal. The author selected a renovation and expansion project of an office building in a university of Guangzhou for empirical research. This was to combine the DeST software and the proposed calculation model to estimate the carbon emissions of the office building at each stage. The effectiveness of calculation model has been verified by the case study. The estimation results showed that the carbon emissions in the stages of building material production, transportation, construction and installation, O&M, and demolition and disposal accounted for 13.38%, 0.09%, 0.79%, 84.15%, and 1.60% of the $LCCO_2$ emissions respectively. It can be seen that the building material production stage and the O&M stage of buildings are the phases with the highest carbon emissions and the greatest emission reduction potential.

Since then, some scholars have established a variety of carbon emission calculation models to calculate the life cycle carbon emissions of residential building (Mao, 2018) and commercial building (Zou, 2020). In addition, scholar Xiao (2021) have established $LCCO_2$ emission and LCC estimation models for the green building evaluation system. The rationality of the model has been verified based on an actual building case. However, the above research is based on the existing buildings, problems such as difficulty in data acquisition and large amount of calculation may occur by using formula for estimating $LCCO_2$ emission amount, which will influence the accuracy of calculation. In addition, as a cutting-edge research area, there is currently few research on the $LCCO_2$ emission estimation during the building design stage, nor on a green building assessment practice project.

2.3. Multi-criteria decision analysis

2.3.1. The concept of multi-criteria decision analysis

As a sub-field of management science or operations research, MCDA has attracted increasing attention from researchers over 50 years (Roy, 1990; Govindan and Jepsen, 2016). It is a technique for making decisions in different areas by considering a series of alternatives, and multiple quantitative and qualitative criteria. This is to highlight the diverse perspectives of the actors involved in the decision-making process (Figueira *et al*., 2005). Criteria such as attributes, objectives or goals are then formulated. Being proved the effectiveness in transportation sustainability, MCDA can be used to solve sustainability-related issues (Kozlov and Sałabun, 2021).

2.3.2. The importance of multi-criteria decision analysis

MCDA can help architects and designers find the best combination and properly weigh a set of design parameters to improve building performance (de Almeida Rocha *et al*., 2020). This technique is designed to assess alternatives based on multiple criteria by using systematic analysis to support decision-making on different issues (Belton and Stewart, 2010).

2.3.3. The category of multi-criteria decision analysis

Various MCDA methods and their corresponding applications have been highlighted in various academic texts. Mendoza and Martins (2006) proposed different classification of MCDA methods, whilst Hwang and Yoon (1981) divided MCDA methods into two categories based on the size of a considered alternative set. The first method was the Multiple Attribute Decision Making (Hereinafter referred to as MADM) method, which is adopted for problem-solving with a pre-defined set of discrete alternatives. MADM involves elections that do not require mathematical analysis. It is normally used to solve problems in discrete spaces, especially the evaluation and selection problems of limited number of alternatives (Hartati *et al*., 2010). The second method is the Multi-Objective Decision Making (Hereinafter referred to as MODM) method, which designed to solve problems where the alternatives are not pre-defined. Designed by using the best alternative, MODM involves the design of using mathematical optimization techniques to solve problems in continuous space, such as those in mathematical programming. In addition, this type of MCDM is applicable to an infinite number of alternatives, answering questions about what and how much. Triantaphyllou (2000) pointed out that confusions may occur as the terms of MADM, and MCDA (or MCDM) have been used interchangeably in some of the literatures. Belton and Stewart (2012) suggested another classification considering three categories of MCDA methods:

(1) The Value Measurement Models, where alternatives have been assigned respective numerical scores for indicating the extent to which a specific alternative is superior to another.
(2) The Goal, Aspiration, or Reference Level models, which attempt to identify the alternative that comes closest to realize some pre-determined goal or aspiration.

(3) The Outranking Models, which are based on pairwise comparisons of alternatives on each criteria (or comparisons to pre-determined norms). Procedures for aggregating and leveraging the information are followed to demonstrate the strength of the evidence for supporting the superiority of one alternative over another (Mendoza and Martins, 2006).

2.3.4. ELECTRE method

As an outranking approach in MCDA methods, the ELECTRE family has been developed for more than 40 years. The acronym ÉLECTRE stands for: ÉLimination Et Choix Traduisant la REalité (Elimination and Choice Translating Reality) (Wikipedia, 2024). Benayoun *et al.* (1966) proposed the first ELECTRE method by reporting on the work regarding a specific real-world problem for SEMA, a European consultancy company. This method has been described in detail by (Roy, 1968) two years after its appearance and renamed as ELECTRE I later. Figueira *et al.* (2005) claimed that this method was sometimes unofficially named as ELECTRE Iv (v for veto), when veto thresholds were being considered. Over the next two decades, ELECTRE methods were then developed into several versions, e.g., ELECTRE II (Roy and Bertier, 1971), ELECTRE III (Roy, 1978), ELECTRE IV (Roy and Hugonnard, 1982), ELECTRE TRI (Yu, 1992; Roy and Bouyssou, 1993), ELECTRE IS (Roy and Bouyssou, 1993). When Almeida-Dias *et al.* (2010) proposed a new version of ELECTRE TRI-nC as an extension of ELECTRE TRI-C. The original version of ELECTRE TRI was renamed as the ELECTRE TRI-B (Figueira *et al.*, 2010). Roy and Vincke (1984) indicated that the concept of pseudo-criteria has been considered in various versions of ELECTRE methods except ELECTRE I, Iv, and II. This concept allows modeling imperfect knowledge due to indifference and preference thresholds. This may be caused by uncertainty, imprecision, and mis determination of some data.

Each ELECTRE version is different in its operation regarding the types of problems they can be applied to. Roy (1976) defined four types of MCDA problems, representing different goals related to how the decision maker (DM) analyzed the problem as well as what type of outcome was desired. It can be noted that ELECTRE I, Iv and IS are applicable to the so-called choice problematic or problematic α with the goal of selecting the smallest set of optimal alternatives. Besides, ELECTRE II, III, and IV are designed with the aim of developing an ordering of alternatives from best to worst, which is called the ranking problematic or problematic γ. The true criteria are being used in ELECTRE II, while pseudo criteria are adopted in the other two.

Differences between ELECTRE III and ELECTRE IV exist in many ways, particularly with the criteria weights are not being used in the latter one. With the goal to assign alternatives to a set of pre-defined categories, the ELECTRE TRI, TRI-C, and TRI-nC are used for sorting problematic, also known as problematic β. Being included in the other three methods, the final problem is called the description problematic or problematic δ, which can be considered separately if only a description of the problem exists (Govindan and Jepsen, 2016).

Two stages are normally existing in the ELECTRE methods. 1. In the stage of aggregation, the concepts of concordance and discordance are applied to perform pairwise comparisons of alternatives in a multi-criteria aggregation procedure (Hereinafter referred to as MCAP). The alternatives are being characterized according to their performance on each criteria. In the approaches of sorting problematic α or problematic γ, alternatives are compared. However, in the problematic β approach, the considered alternative is compared with a set of reference alternatives. These reference alternatives are characterized by the specification of different criteria. Depending on the specific approach in problem, one or more outranking relations can be constructed resulting from the pairwise comparison of alternatives. As a preferential model, three types of cases are being considered in an outranking relation, e.g., preference, indifference, and incomparability. 2. In the stage of exploitation, an exploitation procedure (Hereinafter referred to as EP) specific to the ELECTRE approach exists, which is used to exploit the outranking relations constructed by the MCAP. Then the results expected for a given problem can be presented (Figueira *et al*., 2013; Govindan and Jepsen, 2016).

To facilitate the calculation, Mousseau *et al.* (2000) claimed that a series of software packages have been developed for several ELECTRE methods, e.g., ELECTRE IS, ELECTRE III–IV, and ELECTRE TRI. The criteria weights regarding the ELECTRE TRI model can be inferred by the users from examples of assignments. Some other general software implementations are related to ELECTRE. Kiss *et al.* (1994) proposed ELECCALC to estimate the parameters based on the ELECTRE II model. Dias and Mousseau (2003) indicated that IRIS3 can infer the parameters based on a modified ELECTRE TRI method. Figueira and Roy (2002) applied SRF4 to calculate the criteria weights for ELECTRE methods. In addition, some other specific software implementations of ELECTRE-based methods have been in practical use, such as SADAGE (López and Sánchez, 2005; Leyva López *et al*., 2008), ESSE (Vlahavas *et al*., 1999), Skills Evaluator (Anestis *et al*., 2006) and Decision Deck project.

As for ELECTRE I method, it can be commonly seen by using formula calculation (Liu and Wan, 2019; Xiao, 2021). Problems of long-time calculation, data missing, and data error may exist that affect the accuracy of the assessment results. Some other studies adopted software for ELECTRE I computation. Problems may exist in application of the software due to the language barrier and software acquisition failure. To avoid the above possible problems when using ELECTRE I method, some other automatic calculation methods can be applied in Excel, e.g., ELECTRE Toolkit for Excel (ELECTRE Toolkit, 2024), XLSTAT (XLSTAT, 2024b), which largely reduce the computing time and ease the burden for users. Govindan and Jepsen (2016) divided energy management into two categories, one is large scale energy management, the other is energy management within a building, e.g., HVAC system. The latter category normally addressed the issues involved HVAC system selection, HVAC system working conditions determination, building renovation strategies selection, and residential building energy identification, all of which contribute to the indoor environment and energy consumption to some extent. Regarding the decision problem related to building energy consumption, some scholars adopted different ELECTRE methods. Roulet *et al*. (2002) proposed a method for rating or ranking office buildings renovation options. This method recommended the use of principal component analysis (Hereinafter referred to as PCA) to rate alternatives based on different energy consumption and criteria related to indoor comfort. When other considerations such as environmental impacts and costs should be included, the ELECTRE III or IV is recommended. The authors used ELECTRE III to rank six office building on eight criteria. Mróz and Thiel (2005) applied ELECTRE III to compare the four integrated cooling-heating systems in an office building. These four systems have been assessed from the perspective of energy consumption, CO_2 emissions, investment costs, and exploitation costs. Avgelis and Papadopoulos (2009) adopted simulation software to model six different HVAC systems operation in a university building. This is to measure their impact on energy consumption, thermal comfort, indoor air quality, economic and environmental costs in the studied building. Three different scenarios, such as energy costs and inflation, economic and life-cycle costs for obtaining a system, have been considered when using ELECTRE III to rank the specific HVAC systems. Catalina *et al*. (2011) used ELECTRE III to select a preferred multi-source energy system for a residence building. Three criteria have been considered, such as energy reduction, payback time, and CO_2 reduction. This is to rank the 144 alternatives in this specific case.

2.3.5. Entropy weight method

Entropy weight is a parameter that describes the degree of proximity of different schemes on a certain attribute (Zhou *et al*., 2016). According to entropy theory, the criteria contribute more to the decision if the information entropy of a given criteria is low, which means that these criteria should be given a larger weight. The information entropy has been used to objectively determine the criteria weights in some studies related to MCDA problem solving. Zamri and Abdullah (2014a) used the interval 2-entropy definition to choose the optimum flood control project by using the IT2FTOPSIS weighting process. This study informed that the water diversion scheme had the highest proximity coefficient. Zamri and Abdullah (2014b) proposed a new linguistic variable. This considered both the positive and negative ideal approaches for the IT2FN concept with interval 2-entropy weights. To deal with MCGDM problems, Qin and Liu (2015) introduced a combined weighting method on the basic of ranking value and entropy with IT2 FN information. The algorithms of the above studies are extremely complex although they have been proven to be effective and practical. Therefore, in this research project, the basic entropy weight method has been proposed to determine the weights of multiple criteria for its effective calculation (Shen, 2019; Li *et al*., 2021).

2.4. Summary

In order to continuously improve Chinese green building evaluation system, a number of scholars are committed to carry out comparative study on the green building evaluation standards that have been used in China and other developed countries, including evaluation contents, scoring methods and weighting systems, etc. They are hoping to put forward some suggestions on the improvement of Chinese standards. However, the above comparative study on the green building evaluation standards showed that the relevant research has not kept up with the development of new policies. Firstly, the above studies mainly focused on the general content’s comparison, rather than a detailed analysis for a certain criterion, such as the relevant provision of a certain building component (e.g., external shading). Secondly, a systematic study on ASGB-2019 that currently being used in green building evaluation practice has not yet been in study, nor has a longitudinal study on China's three versions of green building evaluation standards been investigated. Thirdly, most of the studies are limited to the theoretical research of evaluation standards and policies, lacking the more valuable empirical research on the current practice of green building assessment in Chinese building industry.

With the popularization of external shading design in construction industry, many scholars carried out studies to assess the performance of various external shading facilities. This is to highlight the energy-saving impact and thermal performance of various external shading designs, with the consideration of energy-saving rate, lighting, ventilation, indoor thermal comfort, etc. The above simulation studies revealed that integrating solar shading devices can achieve substantial energy-savings and better performance of lighting and indoor thermal comfort. It should be noted that most of the assessment on the external shading equipment are conducted after the building is completed. Currently, there are few studies on this specific issue during the building design stage, nor based on a green building assessment practice. Further, only a small number of scholars applied LCA and LCCA methods to analyze the economic and environmental performance of external shading designs. As a cutting-edge analysis method for environmental assessment of buildings, $LCCO_2A$ has not yet been used to analyze the carbon emissions of building shading components. It is also rare to assess and analyze a building from the comprehensive perspectives of energy-saving, economy, and environment, let alone the multiple criteria assessments of the building shading devices from the above three points of view. Finally, the research on the simulation analysis of the external shading design by using the software on GBSWARE technical platform mainly focused on its energy-saving and lighting impact on the building, whilst the impact of the ventilation, thermal comfort, carbon emissions and other aspects on the building is still lacking. This is also worthy of further exploration for a multi-criteria assessment regarding the external shading devices, which is extremely valuable in both theoretical research and evaluation practice.

As an effective outranking approach in MCDA method, different ELECTRE techniques have been used to assess alternatives based on multiple criteria. In the building energy conservation research area, scholars mainly adopted ELECTRE III for ranking and selecting the optimum HVAC system on multiple assessed criteria. There is currently no research for the multi-criteria assessment for other building components by the ELECTRE methods. This is well worth to expand the research scope by using other versions and software of the ELECTRE family. This premise sets the stage for the next few chapters with in-depth discussion on the comparison of Chinese green building evaluation standards and the assessment practice focused on external shading, the energy-saving, economic and environmental impacts of fixed external shading designs on a green educational building project, as well as MCDA on the proposed criteria for selecting a preferred fixed external shading device.

Chapter 3. Methodology

This chapter explains and justifies the research methodology chosen for this study. A variety of research methods have been applied in this research project. To achieve the stated objectives, the mixed research methodology has been used in this research project, combining a series of quantitative and qualitative approaches. Qualitative approaches include literature review and case study, involving collection of non-numerical data to gain a deeper understanding of fixed external shading assessment in Chinese context. Quantitative approaches include comparative study and simulation analysis (e.g., BESI, LCCA, CEEB, ELECTRE method), allowing for the collection of numerical data. By collecting and analyzing both quantitative and qualitative data in the same research project, a more meaningful conclusion of assessment method and a preferred fixed external shading design has been drawn. All the stages of the research work are given in the following flowchart (see Figure 3.1):

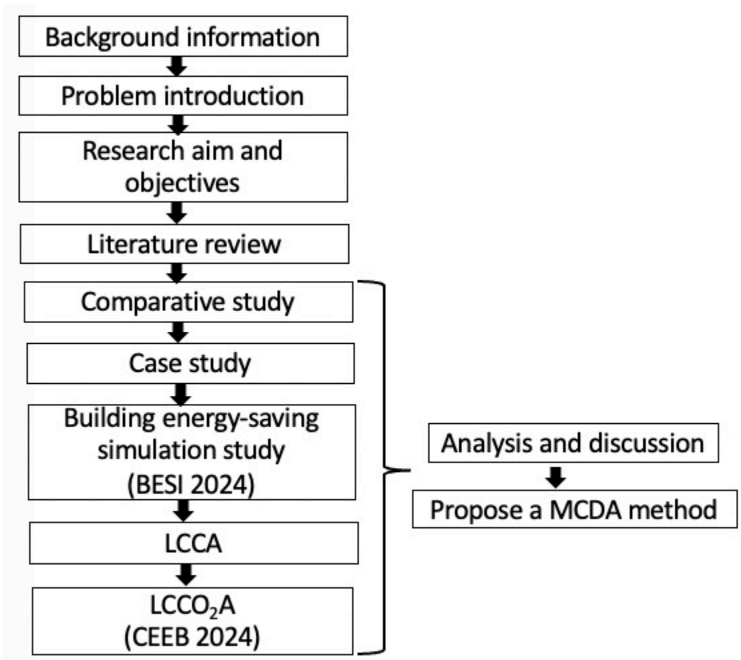


Figure 3.1 Research flowchart

3.1. Literature review

Literature review of this research project has been conducted mainly from the perspectives of green building assessment, external shading design assessment and multi-criteria decision analysis. Relevant academic literature has been collected from multiple databases (e.g., Science Direct, Web of Science, Google Scholar, CNKI of China, etc) by using a couple of keywords, such as ‘green building assessment/evaluation’, ‘external shading design assessment’, and ‘MCDA’, etc. In addition, relevant assessment reports, national and regional evaluation standards have been included. In terms of green building assessment, the development and basic assessment contents of several well-known green building evaluation standards have been reviewed, such as BREEAM in UK, LEED in US, CASBEE in Japan, DGNB in Germany, Green Mark in Singapore, and green building evaluation systems in China. As for the external shading design assessment, the research paper related to shading design categories, shading product classification, materials of shading devices, and the assessment of external shading design from various perspectives have been reviewed. Besides, the review of multi-criteria decision analysis mainly focuses on the categories of MCDA method, and its outranking approach named ELECTRE method.

3.2. Comparative study

A series of comparative studies have been conducted in this research project, from the stage of shading-related provisions investigation in Chinese green building evaluation standards, to the stages of energy-saving, economic and environmental impact assessment of fixed external shading designs.

3.2.1. Shading-related provisions investigation in Chinese evaluation standards

The first comparative study has been applied in two steps of provision investigation stage by reviewing relevant evaluation standards. The standards to be reviewed are collected by online searching of relevant government websites. The first step is the comparison of the general contents among ESGB-2006, ASGB-2014 and ASGB-2019, with respect to their corresponding application scope, evaluation timeline, evaluation objects, evaluation content, rating methods and certification levels. This step also includes an investigation and discussion with several respondents to explore the existing problem during the promotional process of relevant standards and industry development. The second step is a detailed comparison regarding external shading related provisions amongst the aforementioned standards. This includes the evaluation criteria, provision contents and scoring methods, etc. Issues related to shading provisions in Chinese standards have been illustrated through comparative study and investigation with relevant respondents.

3.2.2. Energy-saving impact assessment of fixed external shading designs

The second comparative study has been carried out during the energy-saving impact assessment stage, by comparing the values of energy-saving rate of building envelope regarding the 21-shading cases that planned to be applied on the studied educational building project. The above values are collected through building energy-saving simulation by using BESI 2024. This comparative study has been divided into four categories based on the type of fixed external shading design (e.g., horizontal shading, vertical shading, baffle-type shading, and integrated shading). This is to explore the influence of protruding dimension of shading devices on the values of annual comprehensive heating and cooling energy consumption, thus derive corresponding energy-saving rate of building envelope. The optimum shading design with the highest energy-saving impact has then been generated through comparative analysis for subsequent assessment study.

3.2.3. Economic impact assessment of fixed external shading designs

The third comparative study has been conducted during the economic impact assessment stage. Through a series of comparison, the present values (Hereinafter referred to as PV) of costs at each material life cycle stag, as well as the NPV of LCC (also can be regarded as initial investment) of six shading options have been determined from high to low. The above PV are collected by conducting LCCA. The obtained NPV of LCC of the six shading options are to conduct the comprehensive assessment in the subsequent chapter.

3.2.4. Environmental impact assessment of the fixed external shading design

The fourth comparative analysis has been conducted during the environmental impact assessment stage. Through a series of comparison, the carbon emission amounts at each building life cycle stage and the total $LCCO_2$ emission amounts of six shading options have been generated from high to low. The above carbon emission amounts are collected through building carbon emission simulation by using CEEB 2024. The obtained $LCCO_2$ emission amounts of six shading options are to conduct the comprehensive assessment in the subsequent chapter.

3.3. Case study

The use of a case study is believed to be an empirical method with the aim of researching a contemporary phenomenon in a particular setting (Benbasat et al., 1987; Eisenhardt, 1989;

Runeson and Höst, 2009). Due to the unclear boundary between the phenomenon and its context, Runeson and Höst (2009) pointed out that case study was capable to solve the research problem in the area of software engineering. Zave (1997) stated that in order for the methodology to be confirmed as a solution to the engineering problem, then it would need to be compared to alternative methodologies. Therefore, the case study has been applied to analyse a typical conceptual design example. The 3D building model and the relevant assessment reports of the studied educational building are collected through investigation with green building consulting company D in Shenzhen. The reason for choosing this building case is it is a small and medium-sized public building. Its rectangular shape structure is convenient for the analysis of single building element variables. Moreover, its location belongs to hot summer and warm winter climate region, which meets the climatic requirements of this study. More importantly, the building is currently in the design and evaluation stage, relevant information regarding architectural design and assessment are in line with the current green building assessment industry practice, keep up with the latest industry development in China. This also facilitates discussions with relevant personnel in charge of the construction project. This building case is used for the whole research project, including the investigation of external shading assessment in the current evaluation standards, the assessment of building energy-saving effect, economic impact, environmental performance, and multi-criteria assessment. The detailed building information are illustrated below.

3.3.1. Overview of studied educational building project

Due to different geographical condition, China is divided into five typical climate regions, namely Severe cold, Cold, Hot summer and cold winter, Hot summer and warm winter, Temperate (Wang *et al*., 2015) (see Figure 3.2), resulting in large regional differences between different climate zones.

Figure 3.2 Five climatic zones and relevant typical cities in China

(Source: Wang *et al*., 2015.)

(1) Building and geographical location

The project adopted for case study is a hypothetical three-story kindergarten building framed in structural steel, which is in charge of the investigated green building consulting company D. The respondent C (green building evaluation expert) clarified that the studied kindergarten project is in the design stage. It is expected to start construction in late 2024 and will be completed between 2025 and 2026. This project has been certified as One-star green building in the green building pre-evaluation stage in Shenzhen. This case study has been used to explore the whole practice process of green building evaluation in China. In the meantime, it has been used throughout the subsequent analysis of energy-saving, economic (LCCA) and environmental (LCCO_2A) impact, as well as the comprehensive criteria assessment regarding various fixed external shading designs.

The studied green educational building is located in the Pingshan District of Shenzhen, a city in the southern area (Area B) of the hot summer and warm winter region in China (Table 3.1 listed the detailed division of urban areas in this specific climate region). The hot summer and warm winter climate region mainly refer to the southern part of China, including provinces of Guangdong, Fujian, Guangxi, Hainan, etc. It is noted that the cities with large number of green building projects in this specific climate region are Guangzhou, Shenzhen, Zhuhai, Foshan, etc., which belong to large or medium-sized city. In this research, Shenzhen city is selected as the studied geographical area. The internal green building self-evaluation report of this educational project indicated that the assessment scope involved in green building evaluation was the kindergarten building (as showed in the red line area in Figure 3.3). The building type is Category A public building (see Table 3.2) (DOHURD-GD, 2020).

Table 3.1 Thermal engineering zone of buildings in the representative cities of Guangdong Province in China

Climate zone		**Representative cities**
Hot summer and cold winter region		Shaoguan
Hot summer and warm winter region	Northern Area (Area A)	Meizhou (Meixian District, Pingyuan County, Xingning City, Jiaoling County, Meijiang District), Heyuan (Dongyuan County, Lianping County, Heping County, Longchuan County, Yuancheng District), Qingyuan (Yingde City, Lianzhou City, Yangshan County, Lianshan Zhuang and Yao Autonomous County, Liannan Yao Autonomous County, Fogang County), Zhaoqing (Huaiji County)
	Southern Area (Area B)	Guangzhou, **Shenzhen**, Zhuhai, Zhongshan, Shantou, Shanwei, Jieyang, Foshan, Huizhou, Dongguan, Yunfu, Chaozhou, Jiangmen, Maoming, Yangjiang, Zhanjiang, Meizhou (Wuhua County, Fengshun County, Dabu County), Heyuan (Zijin County), Qingyuan (Qingxin District, Qingcheng District), Zhaoqing (Duanzhou District, Dinghu District, Gaoyao District, Sihui City, Guangning County, Deqing County, Fengkai County)

(Source: DOHURD-GD, 2020.)

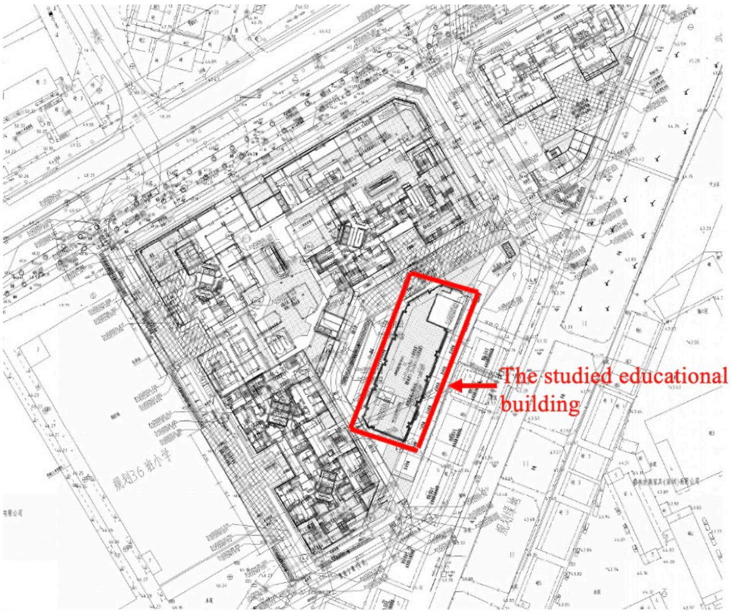


Figure 3.3 The site plan of a One-star kindergarten project in Shenzhen

(Source: Green building self-evaluation report for a One-star kindergarten project)

Table 3.2 Categories and classification criteria for public buildings in China

Building category	Classification criteria
Category A public building	1. A building with a single building area ≥ 300 m^2 2. A building complex with a single building area ≤ 300m^2 but a total building area ≥ 1000 m^2
Category B public building	A building with a single building area of ≤ 300 m^2
Category C public building	Open plan buildings

(Source: DOHURD-GD, 2020.)

(2) Climate characteristic

Energy consumption varies significantly between buildings located in different climatic regions. 'Thermal Design Code for Civil Building GBT50176-2016' (Hereinafter referred to as TDCCB-2016) divides the climate regions of China into five main categories based on the main indicator and the auxiliary indicator (MOHURD, 2016), as shown in Figure 3.2 and Table 3.3. The main indicator refers to the annual average temperature of January ($t_{\mathrm{min}\cdot\mathrm{m}}$) and July ($t_{\mathrm{max}\cdot\mathrm{m}}$). The auxiliary indicator represents the number of days with the annual average daily temperature ≤ 5 °C ($d_{\leq 5}$) and ≥ 25 °C ($d_{\geq 25}$).

Table 3.3 Division indicators and design principles of building thermal design region in China (Hot summer and warm winter region)

First level division region	**Second level division region**	**Regional division indicators**		**Design principle**
		Main indicator	Auxiliary indicator	
Hot summer and warm winter region	Area A	10 °C < $t_{\mathrm{min}\cdot\mathrm{m}}$, 25 °C < $t_{\mathrm{max}\cdot\mathrm{m}}$ ≤ 29 °C	100 ≤ $d_{\geq 25}$ < 200	The heat insulation requirements in summer must be fully met, whilst the heat preservation in winter generally does not need to be considered.
	Area B			

(Source: MOHURD, 2016.)

In this specific climate area, humidity and heat occupies most of the time. To maintain indoor comfort, cooling measures such as air conditioning need to be applied for a long time, causing higher electricity expenditure and CO_2 emission amount compared with other climate regions. With the help of appropriate passive building design measures (e.g., external shading design), sustainable development of the ecological environment can be effectively maintained. Table 3.4 listed the representative cities in this specific area. Summer in this region is long, generally lasts from May to October, with the average temperature between 25 °C and 29 °C in July.

Winter is short, with the average temperature of greater than 10 °C in January. The average temperature throughout the year is higher than 20 °C. It is basically not necessary to consider heat preservation. The number of days with the annual average daily temperature greater than 25 °C is between 100 and 200 (see Table 3.3). This region has sufficient precipitation, with annual precipitation ranging from 1,500 to 2,000 mm. Tropical storms and typhoons are relatively common in summer. The average relative humidity in July is more than 80%. The annual sunshine rate is between 35% and 50%, and the annual sunshine hours is between 1,500 and 2,600 h. Therefore, the design of buildings in this climate area is to meet the requirements of heat insulation, ventilation, and rain protection in summer. It is worth noting that consideration should be focused on cooling needs in summer when designing energy-saving buildings in this specific area, rather than focusing on heating in winter (MOHURD, 2012; Lin *et al.*, 2020). This means that it has higher requirements for building shading and heat insulation. In order to withstand strong solar radiation, corresponding shading designs are suggested (Zhuo, 2015). Table 3.4 listed the meteorological characteristic values of some cities in hot summer and warm winter area.

Table 3.4 Meteorological characteristic values of some representative cities in hot summer and warm winter climate region

City	Annual average temperature (°C)	Average temperature of hottest month (°C)	Annual average precipitation (mm)	Annual average sunshine hours
Guangzhou	22.3	28.8	1800	1412
Shenzhen	**23.0**	**29.0**	**1900**	**1906**
Fuzhou	20.0	28.9	1710	1622
Nanning	22.7	27.0	1500	1812

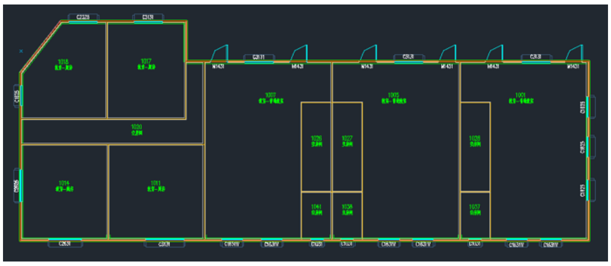
(Source: Zhuo, 2015.)

3.3.2. Construction parameters of the studied educational building

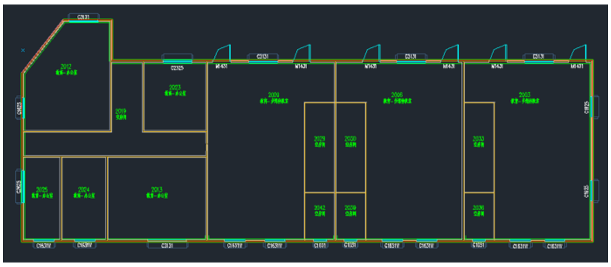
The studied educational building is located at 21°4' north by east, with a height of 11.70m from foundation to roof (sufficient space has been left for services and air circulation), and a plan area of 2,138.25 m^2. The latitude is 23°30' North and the longitude is 113°83' East. Figure 3.4 illustrated the floor plan of the studied educational building.

Through further investigation with green building consulting company D in Shenzhen, the 3D model of the studied educational building (Figure 3.5 and Figure 3.6) was collected for subsequent case study and assessments with respect to the fixed external shading designs. This can be imported into the simulation software on the platform of GBSWAR, such as BESI for energy consumption simulation and CEEB for carbon emission simulation included in Chapter 5, 6, 7. According to the initial construction parameters of the 3D model in BESI 2024, the exterior wall solar radiation absorption coefficient of the studied building is 0.60, the roof solar radiation absorption coefficient is 0.70, and the shape coefficient is 0.27. Table 3.5 and Table 3.6 listed the size parameters of the windows on each building façade and their window to wall ratio. The height of windows is 600mm.

First floor



Second floor



Third floor

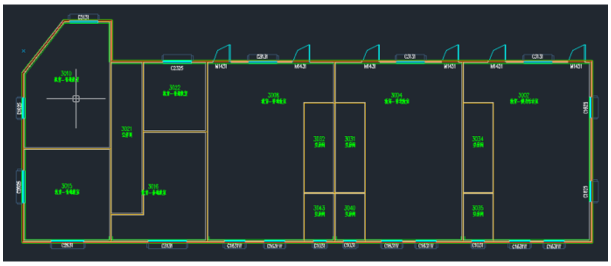


Figure 3.4 Floor plan of the studied educational building

(Source: screenshot from BESI 2024 based on the studied educational building.)

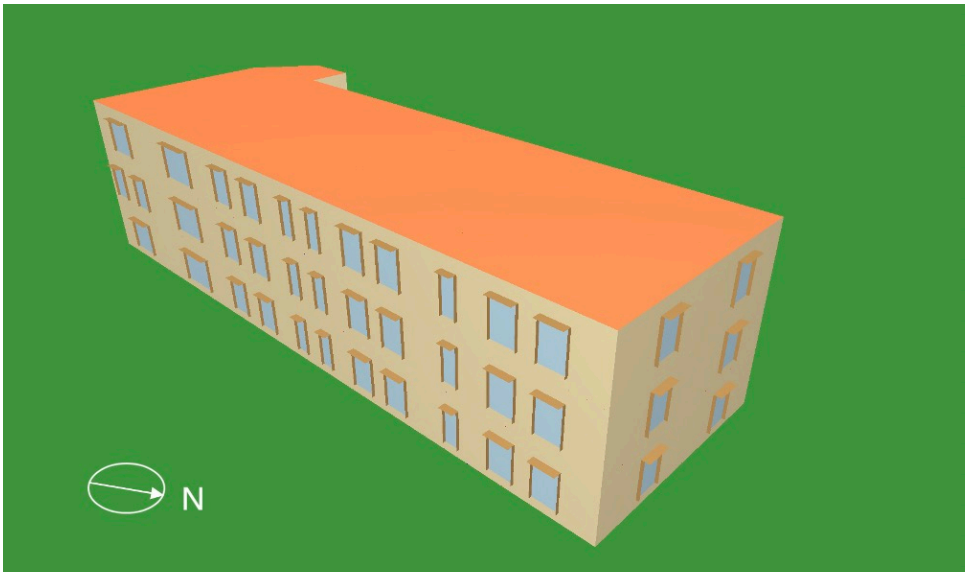


Figure 3.5 3D model of the studied educational building (a)

(Source: screenshot from BESI 2024 based on the studied educational building.

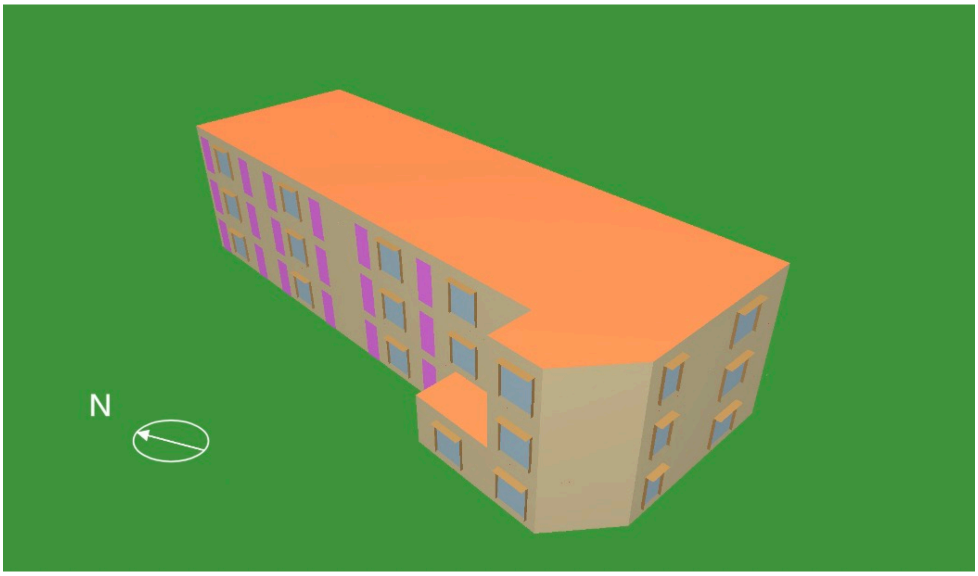


Figure 3.6 3D model of the studied educational building (b)

(Source: screenshot from BESI 2024 based on the studied educational building.)

Table 3.5 Size parameters of the windows on each façade of the studied educational building

Orientation of façade	Number	Size	Floor	Quantity	Area of a single window	Total area of windows
East (140.75)	C1031	1.00*2.50	1-3	9	2.50	22.50
	C1631W	1.64*2.50	1-3	20	4.10	82.00
	C2631	2.60*2.50	1,3	2	6.50	13.00
	C3131	3.10*2.50	1-3	3	7.75	23.25
West (86.44)	C2325	2.31*2.50	1-3	3	5.78	17.34
	C3131	2.31*2.50	1-3	12	5.78	69.36
South (31.80)	C1625	1.64*2.50	1-3	3	4.10	12.30
	C2625	2.60*2.50	1-3	3	6.50	19.50
North (24.60)	C1625	1.64*2.50	1-3	6	4.10	24.60

*Note: Data is derived from BESI 2024 and self-evaluation report based on the studied educational building

Table 3.6 Window to wall ratio on each façade of the studied educational building

Orientation of façade	Area of windows (m^2)	Area of wall (m^2)	window to wall ratio
South	31.80	161.45	0.20
North	24.60	214.11	0.11
East	140.75	542.20	0.26
West	86.70	566.29	0.15
Total	283.85	1484.05	0.19

*Note: Data is derived from BESI 2024 and self-evaluation report based on the studied educational building.

All the envelope properties including roof, external wall, and windows and their corresponding construction elements diagrams are illustrated in Table 3.7-Table 3.9 and Figure 3.7-3.9, which can be obtained from BESI system. The inside temperature has been set to 18°C in winter and 26°C in summer respectively. Feedback from the respondent C indicates that heat preservation does not need to be considered in the cities within Area B of hot summer and warm winter region (see Table 3.1). This subsequent simulation analysis will only be conducted to calculate the value of energy-saving rate of building envelope regarding various external shading designs under cooling conditions in summer.

Table 3.7 Roof attribute parameters of the studied educational building

Building materials		**Thickness δ**	**Thermal conductivity K**	**Thermal resistance R**
Unit		(mm)	W/ (m.K)	(m^2K)/W
Layer 1	Light clay (lightweight mixed planting soil)	500	0.470	1.063830
Layer 2	Fine stone concrete	50	1.740	0.028736
Layer 3	Extruded polystyrene foam board	100	0.030	3.333333
Layer 4	Modified asphalt waterproofing membrane	4	0.230	0.017391
Layer 5	Asphalt waterproof coating	2	0.270	0.007407
Layer 6	Fine stone concrete	30	1.740	0.017241
Layer 7	Reinforced concrete	120	1.740	0.068966
Layer 8	Cement mortar	5	0.930	0.005376
External surface thermal resistance (R_{se}) (m^2K)/W				0.05
Internal surface thermal resistance (R_{si}) (m^2K)/W				0.11
∑R				4.70228
U-value (or thermal transmittance) U=1/∑R (W/(m^2K))				0.2126

*Note: Data is derived from BESI 2024 based on the studied educational building.

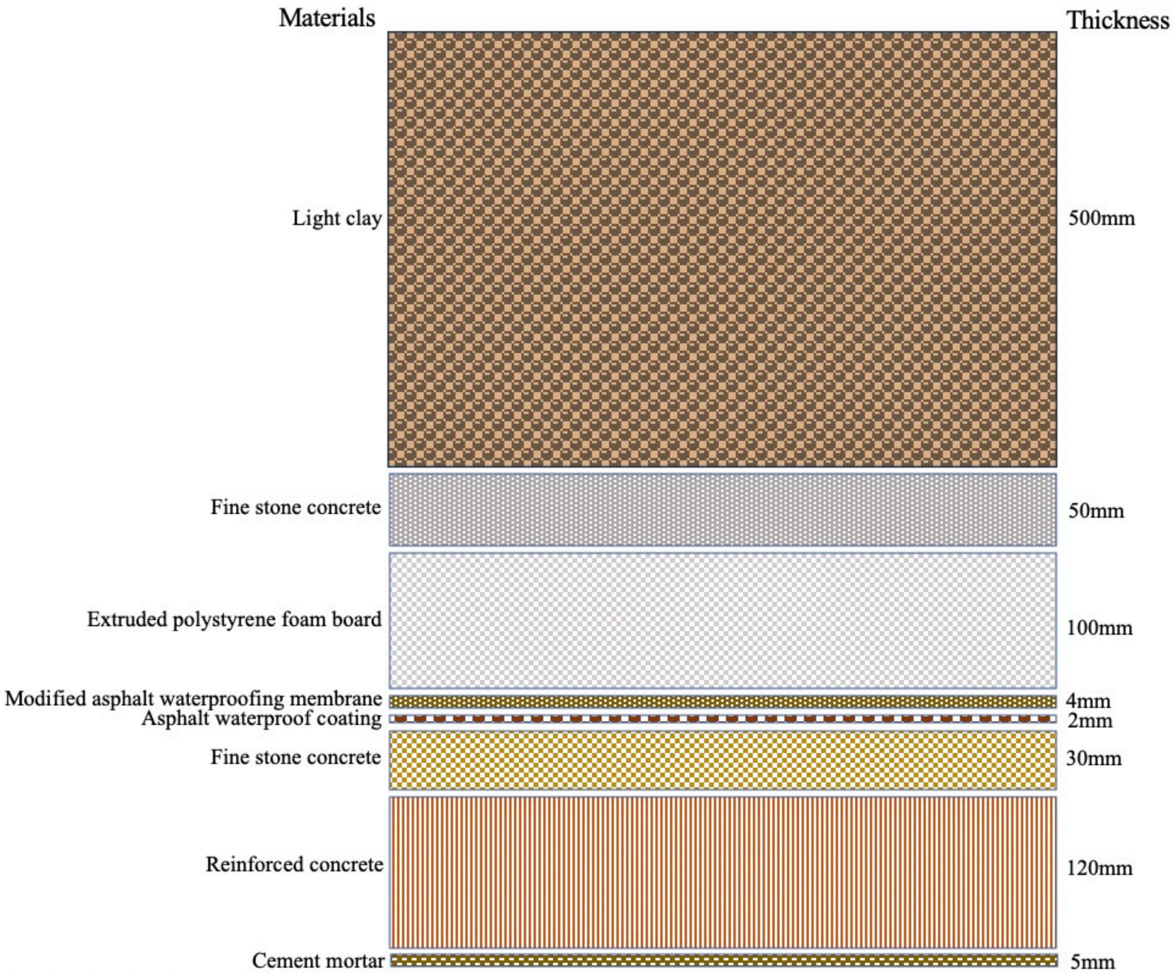


Figure 3.7 Diagram of roof construction elements regarding the studied educational building
(Source: drawn by the author.)

Table 3.8 External wall attribute parameters of the studied educational building

Building materials		Thickness δ	Thermal conductivity K	Thermal resistance R
Unit		(mm)	W/ (m.K)	$(m^2K)/W$
Brick wall - internal insulation				
Layer 1	Putty	5	0.760	0.006579
Layer 2	Cement mortar	5	0.930	0.005376
Layer 3	Aerated concrete blocks	200	0.220	0.909
Layer 4	NEA insulation leveling gel	50	0.030	1.6667
Layer 5	Cement mortar	5	0.930	0.005376
Layer 6	Putty	5	0.760	0.006579
External surface thermal resistance (R_{se}) $(m^2K)/W$				0.05
Internal surface thermal resistance (R_{si}) $(m^2K)/W$				0.11
∑R				2.75961
U-value (or thermal transmittance) U=1/∑R $(W/(m^2K))$				0.3624
Thermal bridge - internal insulation				
Layer 1	Putty	5	0.760	0.006579
Layer 2	Cement mortar	5	0.930	0.005376
Layer 3	Reinforced concrete	200	1.740	0.114943
Layer 4	NEA insulation leveling gel	40	0.030	1.333333
Layer 5	Cement mortar	5	0.930	0.005376
Layer 6	Putty	5	0.760	0.006579
External surface thermal resistance (R_{se}) $(m^2K)/W$				0.05
Internal surface thermal resistance (R_{si}) $(m^2K)/W$				0.11
∑R				1.632186
U-value (or thermal transmittance) U=1/∑R $(W/(m^2K))$				0.6127

*Note: Data is derived from BESI 2024 based on the studied building.

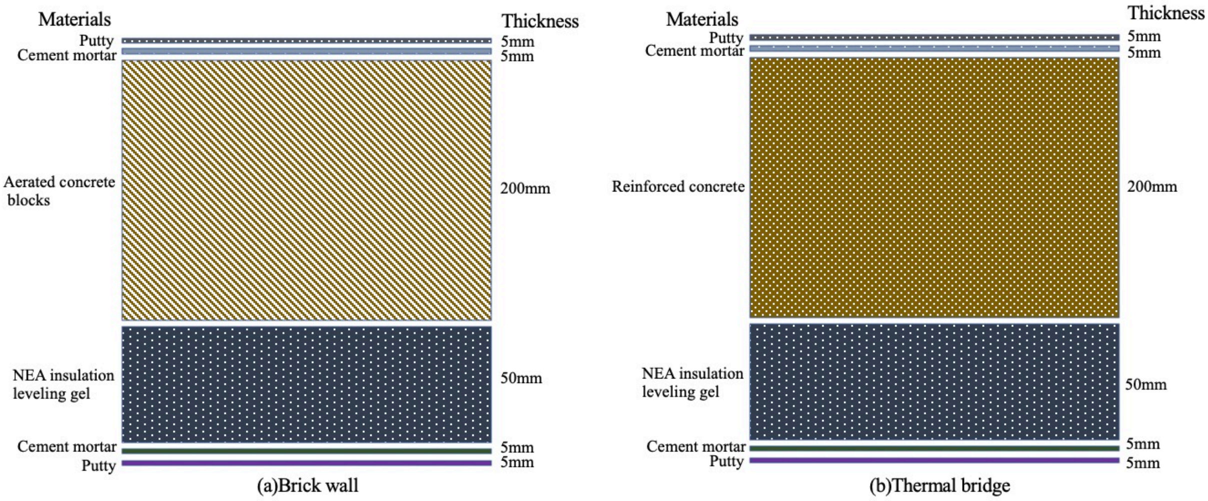


Figure 3.8 Diagram of external wall construction elements regarding the studied educational building

(Source: drawn by the author.)

Table 3.9 Windows attribute parameters of the studied educational building

Window material	U-value (or thermal transmittance) (W/ (m^2.K))
Insulated metal profiles+6mm Medium light transmission Low-E+12mm Argon+6mm Translucent	2.28

*Note: Data is derived from BESI 2024 based on the studied building.

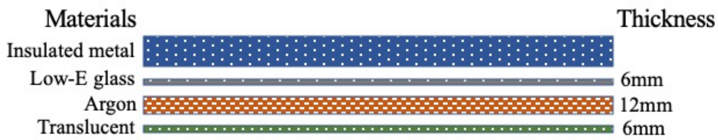


Figure 3.9 Diagram of window construction elements regarding the studied educational building

(Source: drawn by the author.)

According to Table 3.7-3.9, the U-value of the studied educational building is 0.2126 W/(m^{2}K) for roof, 0.3624 W/(m^{2}K) (Brick wall) and 0.6127 W/(m^{2}K) (Thermal bridge) for external wall, and 2.28 W/(m^{2}K) for window. The total window to wall ratio is 0.19 (see Table 3.6). The above U-values meet the requirements of the U-value limit regarding the building envelope listed in the standard of 'Design Code for Energy Efficiency of Public Buildings SJG 44-2018' (Hereinafter referred to as DCEEPB-2018) (see Table 3.10) (SMBHC, 2018). However, the relevant U-value limits in Chinese standard are higher than those of the UK (roof: 0.18 W/(m^{2}K), wall: 0.26 W/(m^{2}K), window: 1.6 W/(m^{2}K)), which shows that there is still much room for improvement in the energy efficiency of Chinese buildings compared with the ones in the UK. This is worthy for further comparative analysis of U-value limits between these two countries by using case study in future research work.

Table 3.10 U-value limits of the building envelope

Components of envelope structure		U-value (W/ (m^2.K))
Roof	Thermal inertness index of the envelope structure D<2.5	≤0.4
	Thermal inertness index of the envelope structure D≥2.5	≤0.8
External wall (Including non-opaque curtain wall)	Thermal inertness index of the envelope structure D<2.5	≤0.70
	Thermal inertness index of the envelope structure D≥2.5	≤1.5
Single-façade exterior windows (including light-transmitting curtain wall)	Window to wall ratio≤0.20	≤5.2
	0.20<Window to wall ratio≤0.30	≤4.0
	0.30<Window to wall ratio≤0.40	≤3.0
	0.40<Window to wall ratio≤0.50	≤2.7
	0.50<Window to wall ratio≤0.60	≤2.5
	0.60<Window to wall ratio≤0.70	≤2.5
	0.70<Window to wall ratio≤0.80	≤2.5
	Window to wall ratio>0.80	≤2.0

(Source: DCEEPB-2018)

3.4. Simulation and data analysis

3.4.1. Building energy-saving simulation

A local Chinese building energy conservation simulation software BESI 2024 is used in this research for building energy-saving impact simulation. This is to obtain the various construction parameters of the studied educational building, as well as input the dimension parameters of fixed external shading devices and other construction parameters for energy-saving simulation study. The reason for adopting BESI 2024 for simulation analysis is that BESI is a commonly used building energy-saving design software in Chinese construction industry (e.g., local design institutes, green building consulting companies, green building evaluation institutions, research institutions, etc.). It is more practical in green building design and evaluation as this research project focuses on Chinese green building evaluation system. Further, different from other English version building simulation software, BESI only has Chinese version, which is conductive to carry out in-depth discussion with relevant respondents in the subsequent research, as Chinese is the main language that being used amongst most local industry participants. The studied 3D building model is collected through investigation with a green building consulting company. Through adjusting the dimension parameters of shading devices, the energy-saving impact regarding 21 fixed external shading designs on the studied green educational building has been assessed, by automatically generating the corresponding values of annual heating and cooling energy consumption and energy-saving rate of building envelope.

3.4.2. Life cycle cost analysis (LCCA)

The initial investments of the fixed external shading devices on the studied green educational building have been assessed by using LCCA method. The reason for adopting LCCA method is that this method can obtain the PV of devices at each life cycle stage through discounting, thereby obtaining the ideal values of corresponding life cycle costs. The shading materials to be studied and their corresponding parameters (e.g., density, lifespan, unit price, etc.) are collected through investigation with the local material suppliers. The six shading cases are determined by considering two shading design (Integrated shading A and Integrated shading I, obtaining by considering the energy-saving impact of 21 shading designs) and three recyclable shading materials (e.g., merbau, aluminum, and polycarbonate, obtaining by investigation with local material suppliers). All the costs have been increased using an assumed inflation rate and then discounted for the base year, with 2.5% inflation rate and 5.04% discount rate that have been collected from the website of Bank of China (BOC, 2024). The price mentioned below have been settled at the current exchange rate of 1:9.24 between GBP and RMB (Alipay, 2024). The PV of costs at each life cycle stage of six fixed external shading devices has been estimated at the discount rate for the projected cash flow over the 50-year building life span. The NPV of the total LCC regarding each shading case can be obtained by summing up the PV of costs at each stage, that is the initial investment of each shading option.

3.4.3. Life cycle carbon emission assessment (LCCO_2A)

CEEB 2024 was applied to estimate and analyze the carbon emission amounts for the whole life cycle of a certain building, covering various stages such as building operation, production, and transportation of building materials, construction, and demolition. This specific software can be used for calculations of building power consumption and carbon emission amounts for green building evaluation practice in China, which has been adopted in the economic assessment and LCCO_2A in this research project. The reason for adopting CEEB 2024 for simulation analysis is that CEEB is a commonly used building carbon emission simulation software in Chinese construction industry. Its practicableness and language characteristics make it smoother for subsequent discussion with relevant respondents. Further, it is a supporting tool for the implementation of Chinese building carbon emission-related standards (GBSWARE, 2024b). The material usages of the six shading cases are obtained through calculation. The carbon emission factors regarding shading materials and coatings are collected through online searching with Baidu website and China products carbon footprint factors database. The carbon emission factors at the carbon sink and building operation stage are collected through reviewing relevant building carbon emission standards. The carbon emission amounts at each building life cycle stage and the total $LCCO_2$ emission amounts of six shading options have been estimated through adjusting the shading material usages and corresponding carbon emission factors in CEEB 2024 system.

3.4.4. ELECTRE I method

The entropy weight method and ELECTRE I have been used for MCDA calculation. The reason for adopting ELECTRE I method is that it can be used to identify a series of alternatives to a decision-making problem. This is capable to obtain an optimal external shading choice amongst limited alternatives with the consideration of multiple assessed criteria. The assessed criteria are determined based on the last three chapters, that is energy-saving rate of building envelope, NPV of LCC, and $LCCO_2$ emission amounts. The corresponding values on the above three criteria regarding six shading alternatives are collected based on the analysis results in the last three chapters. The entropy weight method has been performed through a series of equation calculations in Excel spreadsheet, to determine the weighted coefficients for the assessed criteria. The XLSTAT 2022 plug-in based on ELECTRE I in the Excel spreadsheet has been used to automatically generate a ranking table for the evaluation alternatives. Further, the preferred fixed external shading alternative and the weighting matrix for fixed external shading design assessment have been generated through automatic calculations.

3.5. Summary

This chapter presents a mixed research methodology that has been used in this research project, integrating quantitative and qualitative approaches. The qualitative approaches include literature review and case study, while the quantitative approaches include comparative and a series of simulation study. The detailed data collection instruments, data collection approaches, and data analysis process have been illustrated. This mixed methodology can better achieve the stated aim and objectives, as well as draw a more desired conclusion.

Chapter 4. Comparative Study of Green Building Evaluation Standards in China-with a Focused on External Shading Related Provisions

The discussion on the development and actual implementation of external shading-related provisions amongst ESGB-2006, ASGB-2014 and ASGB-2019 is presented in three sections of this chapter. These sections include a general comparison of three versions of the Chinese green building evaluation standards, a detailed comparison regarding the external shading related provisions amongst the above three standards, and a case study of Chinese green building evaluation. A comparative study and a case study have been applied throughout the whole research process in this part of study. The highlighting of problems and issues existing in the policy promotion process is given in this chapter.

4.1. Comparative analysis among green building evaluation standards in China

The green building evaluation standards in China have been revised three times. ASGB-2019 has been used as the basic criterion for green building evaluation since being introduced in 2019. In February 2023, some provisions have been revised by MOHURD on the basic of ASGB-2019, with a partially revised draft was released for comments to further improve the energy-saving effect of buildings and achieve the targets of building carbon emission reduction. Among a series of energy-saving technologies and measures for green buildings, the external shading designs are a relatively effective passive energy-saving measure. A study on the energy-saving effect of building external shading in hot summer and warm winter area of China revealed that external windows have great energy-saving potential when shading components have been installed. The energy-saving rate can reach about 11.6% and this greatly reduces the energy consumption of air-conditioning. This indicates that the appropriate building external shading design can effectively save energy and reduce carbon emissions. However, from the perspective of evaluation indicator provisions, the external shading neither has received sufficient attention in the three versions of Chinese green building evaluation standards, nor has been modified by the newly revised draft. Therefore, there needs to be an analysis of the Chinese green building evaluation system.

4.1.1. Application scope

As stated above, the green building evaluation system has been revised three times since its inception in 2006. This occurred in 2006, 2014 and 2019 respectively. Table 4.1 listed the application scope of each version.

Table 4.1 Application scope of green building evaluation standards in China

	ESGB-2006	**ASGB-2014**	**ASGB-2019**
Application scope	Residential and public buildings (e.g., office buildings, commercial buildings, and hotel buildings)	Green civil buildings	Green performance of civil buildings

(Source: MOHURD, 2006; MOHURD, 2014; MOHURD, 2019a.)

4.1.2. Evaluation timeline

Specific requirements for the evaluation timeline vary in each version of standard. ESGB-2006 stipulated that the green evaluation of new, expanded and renovated residential or public buildings must be carried out one year after they have been introduced (MOHURD, 2006). In ASGB-2014, the green building evaluation has been divided into design and operation stages. After the government has reviewed the construction design documents, it is key to evaluate the design stage. Moreover, the evaluation of operation stage must be implemented one year after the building has passed the completion acceptance and developed (MOHURD, 2014). As for ASGB-2019, the green building evaluation must be performed after the completion of a construction project, while the pre-evaluation can be assessed after the completion of construction drawing design.

4.1.3. Evaluation objects

Due to the late start of research on the green building evaluation system in China, it is difficult to achieve a detailed division of evaluation objects in a relatively short period of time. All the three evaluation standards mainly focus on individual buildings or building complexes, without many changes to the evaluation objectives amongst the three version (see Table 4.2).

Table 4.2 The evaluation objects of green building evaluation standards in China

	ESGB-2006	**ASGB-2014**	**ASGB-2019**
Evaluation objects	Complexes or individual buildings	Single building or complex buildings	Single building or complex buildings

(Source: MOHURD, 2006; MOHURD, 2014; MOHURD, 2019a.)

4.1.4. Evaluation content

As listed in Table 4.3, there are not many changes regarding the evaluation content between ESGB-2006 and ASGB-2014, apart from the new added criteria named ‘Construction management’ in the latter one. However, a large range of adjustments have been made in ASGB-2019 with respect to the evaluation content, compared to the first two versions. This updated version focuses on the comfort and sustainable development of the living environment.

Table 4.3 The evaluation content of green building evaluation standards in China

	ESGB-2006	**ASGB-2014**	**ASGB-2019**
Evaluation content	Land saving and outdoor environment	Land saving and outdoor environment	Safety and durability
	Energy saving and energy utilization	Energy conservation and energy utilization	Health and comfort
	Water saving and water resource utilization	Water conservation and water resource utilization	Occupant convenience
	Material saving and material resource utilization	Material saving and material resource utilization	Resources saving
	Indoor environmental quality	Indoor environmental quality	Environment livability
	Operation management	Construction management	-
	-	Operation management	-

(Source: MOHURD, 2006; MOHURD, 2014; MOHURD, 2019a.)

4.1.5. Rating methods and certification levels

(1) ESGB-2006

Each category of criteria in ESGB-2006 includes prerequisite items, general items, and preferred items. All the requirements of prerequisite items should be met with regard to residential or public buildings, when conducting green assessments. Green buildings can be categorised on the scale of One, Two or Three star, based on the number of general and preferred items (MOHURD, 2006) (see Table 4.4 and 4.5).

Table 4.4 The number of items required to classify a green building in ESGB-2006 (residential buildings)

Level	**General items (40 items in total)**						**Preferred items (9 in total)**
	Land saving and outdoor environment (8 in total)	Energy saving and energy utilization (6 in total)	Water saving and water resource utilization (6 in total)	Material saving and material resource utilization (7 in total)	Indoor environmental quality (6 in total)	operation management (7 in total)	
★	4	2	3	3	2	4	-
★★	5	3	4	4	3	5	3
★★★	6	4	5	5	4	6	5

(Source: MOHURD, 2006.)

Table 4.5 The number of items required to classify a green building in ESGB-2006 (public buildings)

Level	**General items (43 items in total)**						**Preferred items (14 in total)**
	Land saving and outdoor environment (6 in total)	Energy saving and energy utilization (10 in total)	Water saving and water resource utilization (6 in total)	Material saving and material resource utilization (8 in total)	Indoor environmental quality (6 in total)	operation management (7 in total)	
★	3	4	3	5	3	4	-
★★	4	6	4	6	4	5	6
★★★	5	8	5	7	5	6	10

(Source: MOHURD, 2006.)

(2) ASGB-2014

Each category of criteria in ASGB-2014 includes prerequisite items and scoring items. The bonus item Q_8 named 'Improvement and innovation' have been set in ASGB-2014. The prerequisite items are the clauses that must be met to evaluate the green building. The scoring items and bonus items are the corresponding scores of each criteria, with the full score of each scoring item is 100 points and should not be less than 40 points. Scoring items such as Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, and Q_7 can be calculated through dividing the actual score value of each scoring item by the total score value of all the scoring items applicable to the building and multiplying it by 100 points. The bonus item Q_8 of 'Improvement and innovation' is add-on criterion that encourage performance improvement and innovation, with a maximum score of 10 points. The results of green buildings can be divided into three scales according to the sum between the weighted scores of scoring items and the score of bonus items. The total score of evaluation is calculated according to equation (4.1), in which the weight coefficients of the 7 categories of scoring items are ω_1-ω_7, with reference to Table 4.6 and 4.7. The certification levels of ASGB-2014 are listed in Table 4.8 (MOHURD, 2014).

$$\sum Q = \omega_1 Q_1 + \omega_2 Q_2 + \omega_3 Q_3 + \omega_4 Q_4 + \omega_5 Q_5 + \omega_6 Q_6 + \omega_7 Q_7 + Q_8 \tag{4.1}$$

where

Table 4.6 Criteria and weight coefficient in ASGB-2014

Symbol	Name of criteria	Symbol	Name of weight coefficient
$\boldsymbol{Q_1}$	Score of criteria regarding 'Land saving and outdoor environment'	$\boldsymbol{\omega_1}$	Weight coefficient of criteria regarding 'Land saving and outdoor environment'
$\boldsymbol{Q_2}$	Score of criteria regarding 'Energy saving and energy utilization'	$\boldsymbol{\omega_2}$	Weight coefficient of criteria regarding 'Energy saving and energy utilization'
$\boldsymbol{Q_3}$	Score of criteria regarding 'Water saving and water resource utilization'	$\boldsymbol{\omega_3}$	Weight coefficient of criteria regarding 'Water saving and water resource utilization'
$\boldsymbol{Q_4}$	Score of criteria regarding 'Material saving and material resource utilization'	$\boldsymbol{\omega_4}$	Weight coefficient of criteria regarding 'Material saving and material resource utilization'
$\boldsymbol{Q_5}$	Score of criteria regarding 'Indoor environmental quality'	$\boldsymbol{\omega_5}$	Weight coefficient of criteria regarding 'Indoor environmental quality'
$\boldsymbol{Q_6}$	Score of criteria regarding 'Construction management'	$\boldsymbol{\omega_6}$	Weight coefficient of criteria regarding 'Construction management'

Q_7	Score of criteria regarding 'Operation management'	ω_7	Weight coefficient of criteria regarding 'Operation management'
Q_8	Score of criteria regarding 'Improvement and innovation'		
ΣQ	Total score of evaluation		

(Source: MOHURD, 2014.)

Table 4.7 Weight coefficient of evaluation criteria of green buildings in ASGB-2014

		ω1	ω2	ω3	ω4	ω5	ω6	ω7	$\Sigma\omega$
Design stage	Residential building	0.21	0.24	0.20	0.17	0.18	-	-	1
	Public building	0.16	0.28	0.18	0.19	0.19	-	-	1
Operation stage	Residential building	0.17	0.19	0.16	0.14	0.14	0.10	0.10	1
	Public building	0.13	0.23	0.14	0.15	0.15	0.10	0.10	1

(Source: MOHURD, 2014.)

Table 4.8 The total scores required to classify a green building in ASGB-2014

Level	Total score
One-star	50-60
Two-star	60-80
Three-star	≥80

(Source: MOHURD, 2014.)

(3) ASGB-2019

Similar to ASGB-2014, each category of criteria in ASGB-2019 includes prerequisite items and scoring items. The bonus items named 'Promotion and innovation' have also been set in the new version of standard. The score setting of green building evaluation is listed in Table 4.9.

Table 4.9 The score setting of green building evaluation in ASGB-2019

	Basic scores of prerequisite items Q_0	**Full scores of scoring items**					**Full scores of Promotions and innovation Q_A**
		Safety and durability Q_1	**Health and comfort Q_2**	**Occupant convenience Q_3**	**Resources saving Q_4**	**Environment livability Q_5**	
Score of pre-evaluation	400	100	100	70	200	100	100
Score of evaluation	400	100	100	100	200	100	100

(Source: MOHURD, 2019a.)

The total score of the green building evaluation should be calculated as follows:

$$Q = (Q_0 + Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_A)/10 \tag{4.2}$$

where:
Q is total score of green building evaluation.
Q_0 is the basic score of prerequisite items. When the requirements of all the prerequisite items are met, the basic score is 400 points.
Q_1-Q_5 are the scores of five scoring items.
Q_A is the score of bonus items named 'Promotion and Innovation'.

In ASGB-2019, green building can be evaluated on the scale of Certified, One, Two, and Three star (see Table 4.10) based on the sum of prerequisite items, scoring items and bonus items. When all the prerequisite requirements are met, the evaluation result is Certified. The remaining three certification levels of green buildings should meet the requirements of all prerequisite items, and the score of each category should not be less than 30% of the full score (MOHURD, 2019a). Green buildings should be fully decorated. The quality of the whole decoration project, the selected materials, and the product quality should meet the relevant national regulations and green building technical requirements.

Table 4.10 The total scores required to classify a green building in ASGB-2019

Level	Total score
Certified	All the prerequisite requirements are met
One-star	60-70
Two-star	70-85
Three-star	≥85

(Source: MOHURD, 2019a.)

4.1.6. Problems existing during the policy promotion process

Since the early 1990's, the development of green building evaluation and subsequently the development status has increased substantially. However due to the historic construction concepts, there is still a large divide between the promotion and application of green buildings in China. To explore the existing problems during the promotion and development of Chinese green building evaluation policy, numerous introduction letters have been sent out, and lots of potential respondents in China have been contacted. Five respondents accepted the invitation for investigation regarding relevant professional issues, whose names have been represented by Respondent A-E due to the anonymity of personal information (see Table 4.11). The criteria for selecting targeted respondents are as follows:

(1) Scholars with academic research background in green building.
(2) Evaluation experts with practical experience in green building evaluation.
(3) Designers with experience in designing green public buildings.
(4) Government personnel involved in the formulation of green building evaluation standards and relevant policies.
(5) Structural engineers involved in green building design.
(6) Managers of local architectural design institutes.

Table 4.11 List of respondents

Interviewees	Organization	Position
Respondent A	Architectural Design Institute A in Southern China	Associate dean
Respondent B	School of Architecture in a 985 polytechnic university B of Southern China	Scholar
Respondent C	Third-party green building evaluation agency C in Shenzhen city	Evaluation expert
Respondent D	Green building consulting company D in Shenzhen city	Structural engineer
Respondent E	A branch of design department E in Wanda Group	Design director

Respondent A is an associate dean in a local Architectural Design Institute in Southern China and has participated in lots of green building projects. Respondent B is a scholar and a professor in a 985 polytechnic university located in Southern China, who leads a green building research team in university and has academic and working cooperation experience with green building researchers in universities and designers in architectural design institutes in China. Respondent C is an evaluation expert of green building in a third-party green building evaluation agency in Shenzhen, who has participated in lots of green building evaluation projects in hot summer and warm winter climate region. Respondent D is a structural engineer of building energy-saving design in a green building consulting company in Shenzhen, who have participated in designing lots of advanced green public building projects based on the policies requirements of relevant evaluation standards in this specific climate area. Respondent E is a design director in a local branch of design department in Wanda Group, who has experience in designing the local commercial buildings. All of them have varying degree of understanding of the research and application of green building evaluation standards and related building design policies. Feedback from the investigation highlighted three main problems below:

(1) Insufficient understanding of green building benefits from the public

The benefits of green building largely depend on public attitudes. At the end of the 20th century, Chinese people did not fully understand the benefits of green buildings. With the increase of the environmental pollution and deterioration of air quality in recent years, people began to realize the importance of environmental protection. With the broad concept of environmental protection, public understanding has been limited and hence social responsibility has not been as prevalent as was expected. In addition, scientific research institutions have not quantitatively announced the benefits generated by the development of green building to the public, which has led to their lack of understanding and promotion awareness. Subsequently there has been limited consumer demand for green building.

(2) Insufficient environmental awareness and surveys from architectural designers

Many architectural design practitioners only integrate the development dynamics and trends of the industry into building design. At this time if the feasibility, dissemination, and enforceability of green building design are not comprehensive enough, it will greatly weaken the status of green building design in the minds of people.

(3) Low degree of improvement and innovation of traditional construction technology

The evaluation of green buildings will inevitably involve the construction stage. Therefore, the impact on environmental resources in various fields such as construction decisions, project investment, planning and design, and sustainable technologies, all need to be considered within the scope of the evaluation. The development and evaluation of green building must be based on sustainable development, as the evaluation system and technology cannot be completely independent of traditional construction technology. The concept of sustainable development should be used to improve and innovate traditional construction techniques. The lack of a strong sense of corporate social responsibility has also hindered the vigorous development of green building to a large extent, with many real estate companies ignoring the return rate of buildings on the environment to pursue profits during the development process.

4.2. Comparative analysis of shading related provisions

Shading related provisions among the three versions of Chinese green building evaluation standards are discussed as follow:

4.2.1. ESGB-2006

As illustrated in Table 4.12, ESGB-2006 is divided into two types of evaluation systems, namely residential buildings, and public buildings. Corresponding provisions on shading have been formulated in residential building system from the aspects of 'Land saving and outdoor environment', 'Energy saving and energy utilization', and 'Indoor environmental quality' (MOHURD, 2006). The criteria of 'Land saving and outdoor environment' mainly focuses on greening and shading, which is irrelevant to this research objects. Moreover, the 'Energy saving and energy utilization' criteria aim to set up building shading devices, whilst the 'Indoor environmental quality' criteria focus on adjustable external shading devices. However, neither of these two points has specific requirements for their shading effects. As for public building evaluation system, the use of adjustable external shading devices in green buildings are simply recommended as preferred items for the 'Indoor environmental quality' criteria, which are not mandatory requirements to focus on their shading and energy-saving effects. In addition, ESGB-2006 adopts the measure scoring method, which only determines the evaluation level of a project by calculating the number of general and preferred items that meet the requirements from a qualitative perspective. It not only loses the role of important indicators in reflecting the true degree of greenness (Wang *et al*., 2009), but also lacks quantitative analysis according to different degrees of requirements satisfactions.

Table 4.12 Shading related provisions in ESGB-2006

Building Type	Provisions code	Provision content	Indicator property	Evaluation result
Residential building	**4.1 Land saving and outdoor environment**			
	4.1.16	Permeable surfaces are adopted on non-motorized roads, surface parking lots and other hard paving in residential areas. Landscaping is used to provide shade. The ratio of outdoor permeable ground area should not be less than 45%.	General items	Satisfied
	4.2 Energy saving and energy utilization			
	4.2.4	The natural conditions of the site are utilized, the building shape, orientation, floor distance and ratio of window-to-wall area are rationally designed, to receive better sunlight, ventilation, and lighting for residential buildings, and provide shading facilities as needed.	General items	Satisfied
	4.5 Indoor environmental quality			
	4.5.10	Adjustable external shading devices are used to prevent solar radiation from directly entering the room through the window glass in summer.	General items	Satisfied
Public building	**5.5 Indoor environmental quality**			
	5.5.13	Adjustable external shading is used to improve indoor thermal environment.	Preferred items	Satisfied

(Source: MOHURD, 2006.)

4.2.2. ASGB-2014

As highlighted in Table 4.13, ASGB-2014 has unified requirements for residential and public buildings. On the basis of ESGB-2006, ASGB-2014 further refines the regulations of adjustable shading facilities. The evaluation results have improved from initially meeting the requirements of indicators, to scoring according to the proportion of the shading area (MOHURD, 2014), with a maximum score of 12 points. The sum of maximum scores of the scoring and bonus items in ASGB-2014 is 710 points, of which the maximum score of shading related indicators only accounts for 1.69%. However, this specific regulation still lacks consideration of the energy-saving effect of shading.

Table 4.13 Shading related provisions in ASGB-2014

Building Type	Provisions code	Provision content	Indicator property	Evaluation result
Residential building and public building	**8 Indoor environmental quality**			
	III Indoor hot and humid environment			
	8.2.8	Adopt adjustable shading measures to reduce solar radiation heat gain in summer. Among the transparent parts of exterior windows and curtain walls, if the proportion of area with controllable shading adjustment measures reaches 25%, it will be awarded 6 points. If it reaches 50%, it will be awarded 12 points.	Scoring items	12 points

(Source: MOHURD, 2014.)

4.2.3. ASGB-2019

Similar to ESGB-2014, ASGB-2019 also provides unified requirements for residential and public buildings (see Table 4.14), with specific provisions on shading from two aspects: 'Safety and durability' and 'Health and comfort' (MOHURD, 2019a). The shading related provisions under the criteria of 'Safety and durability' is irrelevant to the shading design and shading effect of external shading facilities. For example, provision 4.1.3, which is a prerequisite item, stipulates that the external shading facilities should be equipped simultaneously with the design and construction of the main structure of the building. Provision 4.2.2, which is a scoring item, states that shading measures should reflect safety protection functions. The criteria of 'Health and comfort', which is scoring item, further subdivides the area proportion and corresponding score of adjustable shading facilities from the perspective of indoor hot and humid environment, with a maximum score of 9 points (see Table 4.15). The sum of maximum scores of the scoring and bonus items during pre-evaluation stage is 670 points (see Table 4.9), of which the maximum score of shading related indicators only accounts for 1.34%. Similar to the previous two versions of the standards, the shading, and energy-saving effects of shading facilities are still not specified in the provision content of ASGB-2019.

Table 4.14 Shading related provisions in ASGB-2019

Building Type	Provisions code	Provision content	Indicator property	Evaluation result
Residential building and public building	**4 Safety and durability**			
	4.1.3	External facilities such as external shading, solar energy facilities, air-conditioning outdoor units, and external wall flower ponds are to be designed and constructed in a unified manner with the main structure of the building, and to meet the conditions for installation, inspection, and maintenance.	Prerequisite items	Satisfied
	4.2.2	Take protective measures to ensure personnel safety: 1. Take measures to improve the safety protection level of balconies, external windows, protective railings, etc. 2. All entrances and exits of the building are equipped with protective measures to prevent accidental falling from external wall coverings, door, and window glass, combining with shading, windshield, or rain protection measures in areas where people pass. 3. Use the site or landscape to form a buffer zone or isolation zone that can reduce the risk of falling objects.	Scoring items	15 points
	5 Health and comfort			
	IV Indoor hot and humid environment			
	5.2.11	Adjustable shading facilities are set to improve indoor thermal comfort and score according to the rules in Table 4.15 based on the proportion of the area of the adjustable shading facilities to the transparent part of the exterior window.	Scoring items	9 points

(Source: MOHURD, 2019a.)

Table 4.15 Scoring rules for the proportion of the area of adjustable shading facilities to the transparent part of the exterior window

The proportion of the area of adjustable shading facilities to the transparent part of the exterior window Sz	Points
$25\% \le Sz < 35\%$	3
$35\% \le Sz < 45\%$	5
$45\% \le Sz < 55\%$	7
$Sz \ge 55\%$	9

(Source: MOHURD, 2019a.)

The above analysis of the three version standards indicates the importance of adjustable shading facilities in green building evaluation is gradually increasing, and its scoring rules are becoming more and more detailed. In ASGB-2014, the scope of adjustable shading measures has been defined. This includes adjustable external shading facilities, permanent facilities (insulated glass laminated intelligent internal shading), fixed external shading integrated internal high reflectivity adjustable shading, etc. (MOHURD, 2014). Feedback from the investigation with the respondent C, D, E (see Table 4.11), showed that the adjustable external shading facilities are not adopted frequently by new buildings in hot summer and warm winter area of China. The main reason for this is that the adjustable designs or the installation of external shading facilities will increase construction costs. Respondent A, B, C, D highlighted that only those buildings which have participated in the green building planning and evaluation will consider external shading designs, to achieve the effect of building energy saving. The external shading design can enrich the building façade, however, those facades with longer exposure to sunlight can be equipped with smaller or no windows to reduce energy consumption losses. There are many options for existing external shading forms, cost of material still has a persuasive effect on builders. For example, even though the adjustable external shading facilities have high shading and energy-saving effect, they are still in low usage due to the high construction and maintenance costs. Judging from most evaluation cases, Respondent C and D stated that builders are more inclined to choose low-cost fixed external sunshades for public buildings. Through the analysis of the above three evaluation standards, the issues of the shading related provisions in Chinese context can be summarized as follow:

(1) The importance of adjustable shading facilities has increased, and the scoring provisions have been gradually refined. However, the proportion of their highest score in the total score is still relatively low, revealing the low importance of shading facilities in green building evaluation.
(2) The qualitative and quantitative provisions on the shading and energy-saving effects of shading facilities haven't been emphasized.
(3) Neither the fixed external shading facilities nor their shading and energy-saving effects have been specified qualitatively or quantitatively in the shading related scoring provisions.

Therefore, to expand the investigation of the shading and energy-saving effects regarding the specific external shading facilities, an in-depth research with the green building consulting company D along with a case study of green building evaluation has been further conducted.

4.3. Pre-evaluation of A green building under the current standard (ASGB-2019)

Implemented by Chinese government as a policy in recent years, green building is supposed to be designed according to the rating level required by the government during the planning and design stage. Feedback from the respondent D pointed out that, a local green building energy-saving design and evaluation software (GBSWARE) has been commonly used by the Chinese design institutes, green building consulting companies, and third-party evaluation agencies, etc.

Feedback from the respondent A indicated that the design institute has outsourced the energy-saving design work to the green building consulting companies, due to the professional and complex characteristics of construction parameters involved in the building design process. Various parameters in the software have been set by the structural engineers until the energy-saving effect of the 3D building design model meets the requirements of the rating level. The corresponding green building rating level will be awarded after the building have passed the assessment. However, due to limited cost budget, respondent D pointed out that some builders do not apply for green building evaluation to gain their corresponding rating levels, even though they meet the certification requirement. In order to investigate the overall assessment regarding the external shading on green public building, a case study of a green kindergarten project in Shenzhen has been performed. Further evaluation of all documental materials has been collected through the current evaluator in the green building consultancy company D.

4.3.1. Evaluation process

According to the information provided by the investigated green building consulting company D (see Appendix A), the general service process of green building evaluation is divided into four stages: namely investment and decision-making stage, engineering design stage, procurement and construction stage, and construction delivery stage. Each stage requires the full cooperation of multiple parties, such as construction project parties, design institutes, green building consulting companies, third-party evaluation agencies, etc. According to the feedback from the respondent C who is in charge of the green building assessment project, the kindergarten project to be investigated has passed a series of pre-construction evaluation processes, such as building energy efficiency evaluation, green building self-evaluation, building energy efficiency design and optimization, construction drawing design and evaluation, etc. This project is currently at the end of engineering design stage, which means that it has firstly passed the pre-evaluation examination from the evaluation experts, secondly is certified as One-star green building, thirdly has received the green building pre-evaluation report.

4.3.2. Evaluation results

According to Provision 3.2.8 of ASGB-2019, a green building is certified as One, Two, or Three star, with the total score Q of 60 points, 70 points, and 85 points respectively, as well as meets the green building technical requirements (see Table 4.16). According to the green building self-evaluation report provided by the respondent C (see Appendix B), all the control items of the project are satisfied with ASGB-2019, the technical requirements for green buildings meet the One-star standard. The score of scoring items with respect to each criteria is no less than 30% of its full score value (see Table 4.16). The total score of the scoring items and bonus items reaches the requirement of One-star standard. Table 4.17 listed the score of each criteria.

Table 4.16 Technical requirements for green building of One, Two and Three star and self-evaluation content for the studied kindergarten project

	One-star	Two-star	Three-star	Self-evaluation content for the studied project
Adopted full decoration	Green buildings at the rating levels of one-star, two-star, and three-star must be fully decorated.			Full decoration
Improvement proportion of the building envelope thermal performance, or the reduction proportion of the building heating and cooling load	Increase the energy saving of building envelope by 5% or reduce the load by 5%	Increase the energy saving of building envelope by 10% or reduce the load by 10%	Increase the energy saving of building envelope by 20% or reduce the load by 20%	The cooling energy consumption of the designed building was 70.05 kWh/m^2, the cooling energy consumption of the reference building is 74.47 kWh/m^2. The reduction ratio of heating and cooling load for the building is 5.95%.
Reduction ratio of external windows heat transfer coefficient of residential buildings in the severe cold and cold regions	5%	10%	20%	/
Level of water efficiency for water-saving appliances	Level 3	Level 2		Level 2
Sound insulation performance of residential buildings	/	The airborne sound insulation performance between the outside and the bedroom, between the bedrooms on both sides of the partition wall (floor), and the impact sound insulation performance of the bedroom floor must reach the average of the low standard limit and the high standard limit.	The airborne sound insulation performance between the outdoors and the bedroom, between the bedrooms on both sides of the partition wall (floor), and the impact sound insulation performance of the bedroom floor meet the high requirements standard limit.	The airborne sound insulation performance between the bedrooms on both sides of the partition wall is 48dB, the air sound insulation performance between the bedrooms on both sides of the partition floor is 48.62dB, and the impact sound insulation performance of the bedroom floor is 62dB.
Reduction ratio of major indoor air pollutant concentrations	10%	20%		>20%
Air tightness of external windows	Comply with the relevant national energy-saving design standards, and the joint between the opening and body of external window should be tight.			The components and connections of external door and window of the building should have sufficient stiffness and load-bearing capacity.

(Source: the investigated green building consulting company in Shenzhen.)

Table 4.17 Self-evaluation scores of a One-star kindergarten project in Shenzhen

	Base scores of prerequisite items Q_0	**Safety and durability** Q_1	**Health and comfort** Q_2	**Occupant convenience** Q_3	**Resources saving** Q_4	**Environment livability** Q_5	**Bonus items of Promotion and innovation** Q_A
Score of pre-evaluation	400	100	100	70	200	100	100
Score of evaluation	400	100	100	100	200	100	100
Score of self-evaluation	400	62	52	32	71	44	17
Total score of self-evaluation Q	67.8						
Total score of evaluation Q	67.8						
Green building rating level of self-evaluation	One-star						

(Source: the investigated green building consulting company in Shenzhen.)

4.3.3. Evaluation of shading related indicators

Table 4.18 listed the assessment results related to shading in the self-evaluation report regarding the studied kindergarten project. The results indicated that the score of adjustable shading facilities related provision is 0, which highlights that the adjustable shading facilities haven’t been adopted in this educational project. However, it is difficult to judge whether the building has been implemented other external shading designs simply relying on the scores in the self-evaluation report, nor has it followed the shading-related provisions of the ‘Design Standard for Energy Efficiency of Buildings GB50189-2015’ (Hereinafter referred to as DSEEPB-2015) (DOHURD, 2015) and the ‘Design Energy Efficiency of Public Buildings in Guangdong Province DBJ 15-51-2020’ (Hereinafter referred to as DSEEPB-GD-2020) (DOHURD-GD, 2020) during the design stage (see Table 4.19-Table 4.20). In order to further investigate whether the external shading design of this studied kindergarten project has complied with the requirements of the above two design standards, an in-depth investigation with the respondent C and D who are responsible for this specific project has been carried out.

Table 4.18 The assessment results of the shading related provisions in the green building self-evaluation report of a One-star kindergarten project in Shenzhen

Attribute item	Indicator item	Provision's code	Provision content	Full score	Results (satisfied/score)
4 Safety and Durability					
Prerequisite items	/	4.1.3	External facilities such as external shading, solar energy facilities, air-conditioning outdoor units, and external wall flower ponds are to be designed and constructed in a unified manner with the main structure of the building, and to meet the conditions for installation, inspection, and maintenance.	/	Satisfied
Scoring items	Safety	4.2.2	Take protective measures to ensure personnel safety: 1. Take measures to improve the safety protection level of balconies, external windows, protective railings, etc., 5 points are awarded. 2. All entrances and exits of the building are equipped with protective measures to prevent accidental falling from external wall coverings, door, and window glass, combining with shading, windshield, or rain protection measures in areas where people pass, 5 points are awarded. 3. Use the site or landscape to form a buffer zone or isolation zone that can reduce the risk of falling objects. 5 points are awarded.	15	15
5 Health and Comfort					
Scoring items	Indoor hot and humid environment	5.2.11	Set up adjustable shading facilities to effectively improve indoor thermal comfort. The score is awarded based on the rules in Table 5.2.11, according to the proportion Sz of the area of the adjustable shading facilities to the transparent part of the external window.	9	0

(Source: the investigated green building consulting company in Shenzhen.)

Table 4.19 Shading-related provisions of DSEEPB-2015

Indicator item	Provision's code	Provision content
3 Building and envelope thermal design		
3.1 General regulation	3.1.4	Architectural design should follow the principle of giving priority to passive energy-saving measures, make full use of natural lighting and natural ventilation, reduce the energy demand of the building combining thermal insulation and shading measures for the envelope structure.
3.2 Architectural design	3.2.5	For the hot summer and warm winter area, hot summer and cold winter area, and temperate area, shading measures for the external windows in all directions of the building (including translucent curtain walls) should be adopted. For the cold area, shading measures are suitable to be adopted in buildings. When installing external shading facilities, the following regulations should be met: 1. Movable external sunshades are suitable to be installed in the east and west directions, and horizontal external sunshades are suitable to be installed in the south direction. 2. The external shading device of the building should consider the effects of ventilation and winter sunlight.
3.3 Building envelope thermal design	3.3.3	The calculation of thermal performance parameters of the building envelope should comply with the following regulations: 3. When external shading components are installed, the solar heat gain coefficient of the external window (including translucent curtain wall) should be the product of the solar heat gain coefficient of the external window (including translucent curtain wall) itself and the shading coefficient of the external shading component. The solar heat gain coefficient of the external windows (including translucent curtain walls) and the shading coefficient of the external shading components should be calculated in accordance with the relevant provisions of the current national standard "Code for Thermal Design of Buildings" GB50176.

(Source: DOHURD, 2015.)

Table 4.20 Shading-related provisions of DSEEPB-GD-2020

Indicator item	Provision's code	Provision content
3 Basic regulation		
/	3.0.2	The energy-saving design of public buildings should optimize the overall design during the planning and design stage, control the volume of the building, optimize the orientation, window-to-wall area ratio, sunshade facade design, and reduce the heat island effect, etc.
4 Building and envelope thermal design		
4.1 General regulation	4.1.6	The transitional space and public space of the building should be set up as open, semi-open spaces and non-air-conditioned rooms. Rooms where personnel are resident should make full use of natural lighting. Natural ventilation should be organized in conjunction with external doors, windows, internal doors, passages, etc. Mechanical ventilation or fans can be supplemented to meet indoor thermal comfort needs when necessary. Thermal insulation and shading measures for the building envelope should be combined to reduce the energy demand of the buildings.
4.2 Architectural design	4.2.4	External windows (including translucent curtain walls) in all directions of the building should comprehensively consider safety, architectural shape, building function and economy. Various effective building external shading measures such as fixed or movable facilities can be reasonably adopted. External shading should be designed according to the following requirements: 1. Corridors, balconies, overhangs, etc. should be included in the shading design. 2. The movable external sunshades are suitable to be adopted in the east and west directions. The horizontal external sunshades are suitable to be adopted in the south directions. 3. The external shading device of the building should consider the effects of ventilation and winter sunlight.
	4.2.14	When glass windows and glass curtain walls are largely adopted in the air-conditioned buildings, intelligent control shading systems and ventilation systems are suitable to be adopted based on building functions and building energy-saving needs. The intelligent control system should be able to sense weather changes and control the shading and ventilation devices in real time based on the needs of indoor personnel.

(Source: DOHURD-GD, 2020.)

Feedback from the respondent D revealed that, apart from following the relevant regulations of DSEEPB-2015 and DSEEPB-GD-2020, the external shading design of this educational building has been implemented. This met requirements for shading measures with respect to Category A: a public building in the hot summer and warm winter climate area. This was mandatory to 'General Code for Energy Efficiency and Renewable Energy Application in Buildings GB55015-2021' (Hereinafter referred to as GCEEREAB-2021) (MOC, 2021) (see Table 4.21). Since the educational building under investigation is still in the design stage, the fixed external shading design can only be viewed through the 3D building model on GBSWARE platform (see Figure 3.5 and Figure 3.6). It can be seen from the 3D model that the fixed external shading panels are installed on all the windows of four building facades.

Table 4.21 Shading-related provisions of GCEEREAB-2021

Indicator item	**Provision's code**	**Provision content**
3 Energy-saving designs of new buildings		
3.1 Buildings and envelopes	3.1.15	Building shading measures should comply with the following regulations: 1. Shading measures should be adopted on the south, east, and west facing external windows and translucent curtain walls of Category A public buildings located in the hot summer and warm winter area and hot summer and cold winter area. 2. The building shading coefficients of the external windows on the east and west facing façades of residential buildings should not be greater than 0.8 in hot summer and warm winter area.

(Source: MOC, 2021.)

Feedback from the respondent C pointed out that the energy-saving or shading effects of the external shading facilities will not be assessed during the pre-evaluation stage of green building assessment. The construction project party only needs to provide the evaluation experts with evidence related to shading scoring information during the construction drawing review process. Scoring requirements for the adjustable shading facilities need to be compiled by ASGB-2019 (see Table 4.14). Segmented scoring is based on the proportion of the area of adjustable shading facilities to the transparent part of the external window, which can reflect the importance of adjustable shading facilities in green building evaluation. However, in addition to the adjustable shading facilities, the other specific provisions haven't been mentioned in ASGB-2019, e.g., fixed external shading devices. This also illustrates the insufficiency focus on building external shading in the green building evaluation. In addition, during the process of building energy-saving design and green building evaluation, the specific energy-saving effects of external building shading facilities have not yet been deeply studied.

This also has seen the economic and environmental benefits of external shading devices being overlooked by all relevant parties.

The subsequent research will investigate the impact of fixed external shading devices on the studied green educational building within hot summer and warm winter climate region. This will consider the performance of energy saving, economic and the environmental impacts. In order to conduct comprehensive assessment for the fixed external shading devices, this research will then propose a multi-criteria assessment method named MCDA, which will generate an optimum external shading solution for stakeholders to make better decision. It is expected that this MCDA method can be implemented to Chinese green building assessment in the future. This can be used for a more comprehensive assessment of various construction projects, including a series of building components, which is worthy of in-depth study in the following chapters.

4.4. Summary

Although the green building evaluation standards have made significant improvements since the first version has been issued in China, problems still existed in the implementation of the new evaluation policy. A series of comparative study have been adopted in this chapter, to explore the development of external shading-related provisions in Chinese green building evaluation standards, e.g., ESGB-2006, ASGB-2014 and ASGB-2019. Several general issues have been identified: 1) Insufficient understanding of green building benefits from the public; 2) Insufficient environmental awareness and surveys from architectural designers; 3) Low degree of improvement and innovation of traditional construction technology. As for the changes regarding external shading related provisions in the three main standards, a detailed review of the shading related policy has been carried out. Problems existing in the shading-related provisions among the three standards are as follow:

(1) The scores of shading-related indicators accounted for less than 1.7% of the total score, reflecting its low importance in green building evaluation.
(2) The importance of adjustable shading facilities was gradually increasing, but the specific regulations on fixed external shading facilities have been overlooked.
(3) There was a lack of qualitative and quantitative scoring rules for the shading and energy-saving effects of shading facilities.

Case study of the specific building project pointed out that only the evidence information related to shading scoring items need to be provided in the actual evaluation practice, rather than a real assessment of the energy-saving or shading effects of the external shading facilities. Further, specific qualitative or quantitative provisions have not yet been formulated into ASGB-2019 for assessing fixed external shading devices. It is also highlighted that the energy-saving effects, economic and environmental performance of the building external shading facilities have not been studied in academic depth, causing them to be overlooked by most of the relevant stakeholders. Hence, further investigation will be conducted in the following chapters, to explore the impact of fixed external shading devices on the studied green educational building project within hot summer and warm winter climate region. The energy saving, economic and environmental effect of fixed external shading designs can be demonstrated. Subsequently, a MCDA method will then be proposed for performing multi-criteria comprehensive assessment to make an optimum decision when choosing the appropriate fixed external shading devices regarding three specific criteria. This assessment method can also be capable to evaluate various construction components on multiple evaluation criteria.

Chapter 5. Energy-saving Impact Assessment

In this chapter, BESI 2024, a local Chinese energy consumption simulation software has been used for simulation analysis. This will demonstrate the practicality of the software system in the process of building energy consumption calculation. For this particular case study, a three-story educational building with 21 fixed external shading designs planned to be installed on the building façade will be assessed. This building is located in the hot summer and warm winter climate of China. Comparison has been conducted among the above shading schemes with respect to the criteria of energy-saving rate of building envelope, so as to obtain the optimum fixed external shading designs with the greatest energy saving effect (illustrated in Figure 5.1). The energy-saving effect is assessed without considering the shading effect from the surrounding buildings, since it is to estimate the studied building's actual full potential for energy consumption. This chapter presents the specific process of energy consumption simulation for the studied educational building, such as the selection of implementation software, description of the case study, shading design configurations, data input, and relevant analysis process, etc. This is to lay the foundation for prioritizing design alternatives when selecting the preferred external shading option during the design iteration process.

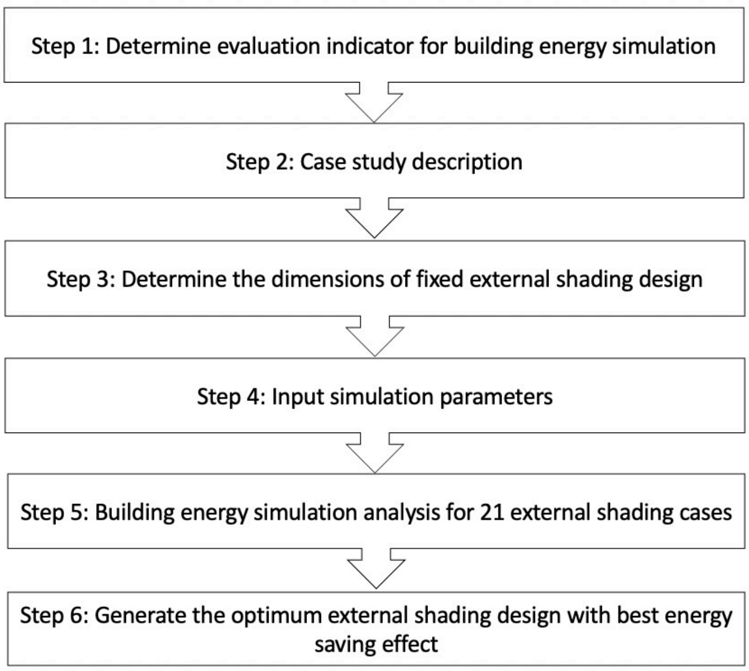


Figure 5.1 Steps of energy-saving effect assessment for fixed external shading design

5.1. Building energy simulation

Energy efficiency is an important feature of green buildings. The energy efficiency pursued by green buildings refers to the efficient use of resources in the whole process from building planning and design, construction, operation, and maintenance, to demolition and recycling, and consequently forms systematic standards. On the one hand, it requires reducing resource waste during planning and design, completing construction with as little investment as possible, and saving energy and land resources. On the other hand, it requires the use of various energy-saving technologies during operation to reduce the building energy consumption, so as to save energy, water resources and materials. In addition, it also emphasizes living in harmony with nature, using the advantages of nature to improve people's living environment as well as reduce environmental pollution (Zhuo, 2015).

5.1.1. BESI 2024

The heat gain and loss of a building is a dynamic process that changes with outdoor environment and time. This requires the use of dynamic calculation methods to calculate the building energy consumption, such as thermal balance method, weighted coefficient method, and the harmonic response method. This is more accurate than the static calculation methods. The commonly used dynamic energy consumption simulation software are DeST (Zhao, 2018), DOE-2 (Li *et al*., 2011), EnergyPlus (Run, 2019), Design Builder (Wang, 2021), TRNSYS, Grasshopper (Jiang, 2020), etc. Although the analysis functions of the aforementioned simulation software are powerful, this part of research adopts a simulation analysis software named BESI, which is widely used in the local construction industry in China and is capable to the studied educational building.

Developed by Beijing Gbsware Co., Ltd., BESI is a professional software that provides energy consumption and energy-saving rate calculation for buildings. This software is built on the AutoCAD platform and based on 3D modelling. Through a series of thermal settings, BESI automatically generates a comparison building based on the designed building, calculates the annual cooling and heat consumption, as well as the heating, cooling, and lighting power consumption regarding the reference building and designed building, thus generates the energy-saving rate. BESI software can be used as a supporting software for energy efficiency certification and green building evaluation (GBSWARE, 2025a). Originally named as BEEC, BESI was developed in mainland China in 2014, and its updated versions have been issued every two years (e.g., BEEC 2014, BESI 2016, BESI 2018, BESI 2020, BESI 2022, BESI 2024). There are 7 basic functions in BESI, including model building, material structure library, thermal settings, system settings, energy consumption calculation, load data and output reports. Compared with previous versions, BESI 2024 has been upgraded in terms of temperature control period, refinement of fresh air schedule, expansion of system terminal equipment, and automatic algorithm of computer room, etc. Several advantages of BESI 2024 are as follow (GBSWARE, 2024a):

(1) Supports the calculation of energy-saving rate stipulated in ASGB-2019, such as energy-saving rate of building envelope structure, and comprehensive energy-saving rate of building heating, cooling, and lighting.
(2) Supports the calculation of whole building energy consumption, such as the calculation targets of main operating energy consumption (heating, cooling, lighting, elevator power and domestic hot water), the renewable energy such as photovoltaic and solar energy are also considered.
(3) Supports the energy efficiency evaluation calculation targets stipulated in 'Standard for building energy performance certification JGJ/T288-2012'.
(4) Refines relevant schedule. This version provides the setting of building heating and cooling period, winter and summer vacations and fresh air schedule, which solves the common problems exist in educational buildings (the need to set up separate duty cooling or heating in some rooms during winter and summer vacations).
(5) Expands cooling equipment, such as supporting Daikin multi-split units, calculating hourly energy consumption, adding floor heating, radiant heating, and radiant cooling terminals, supporting electric boiler heating calculation, as well as regional cooling calculation.
(6) Updates automatic calculation, such as supporting air-cooled units, supporting air source heat pumps and cooling capacity correction at ground ambient temperature.
(7) Supports the use of multiple types of cold (heat) source equipment in the same building.
(8) Powerful composite data analysis and statistical functions, such as checking the year-round hourly dynamic load data at any time.
(9) Annual load sorting and partial load interval hourly statistical analysis.

Due to the upgrade and improvement of BESI 2024 calculation function, especially the support for the calculation of building energy-saving rate stipulated in the new standard, and the refinement of schedule, this part of the study will apply BESI 2024 to perform energy consumption simulations and calculate energy-saving rate of building envelope for each fixed external shading design case.

5.1.2. Determination of assessment criteria

A variety of criteria have been used by the scholars to assess the energy-saving effect of external shading devices on buildings. Liu (2010) adopted the 'total energy-saving rate of building energy consumption' in winter and summer seasons as criteria to assess the energy-saving effect of the external shading facilities. Liu (2011) used the 'lighting energy consumption ratio', 'air conditioning energy consumption ratio', and 'comprehensive energy consumption ratio' to evaluate the impact of external shading on lighting energy consumption, air conditioning energy consumption, and comprehensive energy consumption. Jiang (2020) and Zhou *et al.* (2022) applied the 'building energy-saving rate' as the criteria to assess the impact of external shading components on building energy consumption. Wang (2021) adopted the 'annual comprehensive energy consumption of building' as criteria to evaluate the impact of shading blinds on the energy consumption of an office building. This criterion consisted of the annual lighting energy consumption, the cooling energy consumption of the cooling system, and the heating energy consumption of the building.

(1) Energy-saving rate of building envelope (Φ_{ENV})

During the life cycle of a building, most energy consumption occurs during building operation. Energy consumption can be reduced through passive energy-saving renovation includes heating, cooling, lighting, mechanical ventilation equipment, etc. In ASGB-2019, there are three main requirements related to building load and energy consumption. One is technical requirements (see Table 5.1), the other two are scoring requirements (see Table 5.2). Therefore, to determine the load and energy consumption of green buildings in China, three main indicators need to be considered, namely:

- thermal performance of the building envelope
- building heating and cooling load
- building energy consumption

Table 5.1 Technical requirements for green buildings of One, Two and Three star

-	One-star	Two-star	Three-star
Improvement proportion of the building envelope thermal performance, or the reduction proportion of the building heating and cooling load	Increase the building envelope by 5% or reduce the load by 5%	Increase the building envelope by 10% or reduce the load by 10%	Increase the building envelope by 20% or reduce the load by 20%

(Source: MOHURD, 2019a.)

Table 5.2 Scoring provisions related to building load and energy consumption in ASGB-2019

Indicator item	Provision's code	Provision content
7 Resource Saving		
Energy saving and energy utilization	7.2.4	Optimize the thermal performance of the building envelope, with a total score of 15 points. The scores are awarded according to the following rules: 1. If the thermal performance of the building envelope is better than the current national building energy-saving design standards, and the improvement reaches 5%, 5 points are awarded. If the improvement reaches 10%, 10 points are awarded. If the improvement reaches 15%, 15 points are awarded. 2. If the building heating and cooling load is reduced by 5%, 5 points are awarded. If it is reduced by 10%, 10 points are awarded. If it is reduced by 15%, 15 points are awarded.
	7.2.8	Take measures to reduce building energy consumption, 10 points are awarded. If the building energy consumption is reduced by 10% compared with the current national building energy-saving standards, 5 points are awarded. If the building energy consumption is reduced by 20%, 10 points are awarded.

(Source: MOHURD, 2019a.)

Feedback from the investigation with the respondent C and D indicate that the external shading of a certain building is more relevant to the aforementioned indicator of building heating and cooling load. According to 'Standard for Green Performance Calculation of Civil Building' JGJ/T 499-2018 (Hereinafter referred to as SGPCCB-2018), the proportion of building heating and cooling load reduction should be determined by calculating the value of energy-saving rate of building envelope. The energy-saving rate of building envelope refers to the percentage by which the annual heating and cooling energy consumption of designed building is reduced compared to the reference building, through improving the thermal performance of the building envelope. 3D models of a reference building and a design building are established at the same time in BESI 2024 system based on this specific calculation method. Calculation regarding energy-saving rate of building envelope complies with the following provisions (MOHURD, 2018):

- The annual comprehensive energy consumption of heating and cooling regarding the designed building and the reference building is calculated separately.

- The same version simulation software and typical meteorological data is used for both calculations.

Moreover, the building appearance, internal functional zoning, meteorological parameters, indoor heating and cooling design temperature and humidity of the reference and design building are consistent. The simulation of hourly dynamic energy consumption throughout the year is conducted respectively. Installation of external shading components on the building facades can effectively block direct sunlight, reduce the heat gain from solar radiation entering the room, avoid or alleviate indoor overheating, and thus reduce cooling energy consumption in summer. In addition, part of the sunlight will be blocked from entering the room in winter, leading to lower temperature and increase heating energy consumption during this specific period. Reasonable external shading design should comprehensively consider the needs of summer heat insulation and winter heating preservation. Therefore, this part of research adopts the energy-saving rate of the building envelope (Φ_{ENV}) as an assessment criterion, considering the total energy consumption of cooling in summer and heating in winter. According to the requirements in the SGPCCB-2018, the value of energy-saving rate of building envelope can be calculated based on the equation (5.1) (MOHURD, 2018):

$$\Phi_{ENV} = (E_{bld,ref} - E_{bld,des}) / E_{bld,ref} \times 100\% \quad (5.1)$$

where Φ_{ENV} is the energy-saving rate of the building envelope. $E_{bld,ref}$ is the annual comprehensive heating and cooling energy consumption for reference building (kWh). $E_{bld,des}$ is the annual comprehensive heating and cooling energy consumption for designed building (kWh). The above values can be collected through dynamic simulation by BESI 2024.

(2) Annual comprehensive power consumption (E_{sum})

Apart from the criteria of energy-saving rate of the building envelope, the annual comprehensive power consumption (E_{sum}) can also be used as assessment criteria. The latter one represents the overall situation of the building's energy consumption performance. In a study on energy consumption optimization analysis of public buildings, Wang (2021) pointed out that the energy consumption of the cooling, heating, and lighting systems of public buildings was controllable and greatly affected by sunlight. According to the requirements in the GCEEREAB-2021, the value of annual comprehensive power consumption (E_{sum}) can be calculated based on the adjusted equation below (MOC, 2021):

$$E_{sum} = E_l + E_c + E_h + E_f. \tag{5.2}$$

where E_{sum} is annual comprehensive power consumption of building (kWh/year).
E_l is annual lighting power consumption of building (kWh/year).
E_c is annual cooling power consumption of building (kWh/year).
E_h is annual heating power consumption of building (kWh/year).
E_f is the annual power consumption of fresh air system (kWh/year).
The above values can be collected through dynamic simulation by CEEB 2024. The value of E_{sum} can be used to estimate the potential savings of power consumption and electricity expenditure, which will be further discussed in Chapter 6. It is noting that the geographical scope of this research is located in the hot summer and warm winter climate region of China, where the heat preservation in winter does not need to be considered generally. Therefore, the value of E_h is 0 in the subsequent analysis.

5.2. Case study description

In order to fully highlight the different aspects of the implemented case study, this part of research presents the rationale for the project selection of the studied green educational building. It will also look at the fixed external shading design configurations, simulation data input and relevant operation process. Further simulation analysis regarding the 21 proposed fixed external shading designs will be demonstrated below.

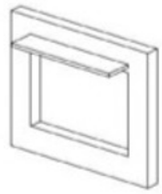
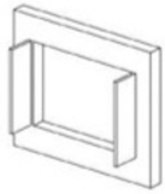
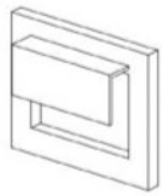
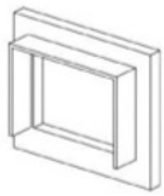
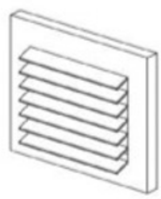
5.2.1. Project selection

In order to implement the concept of green development and promote the high-quality development of green buildings in China, a set of green building evaluation system has been formulated by the government. Among a series of evaluation standards, ASGB-2019 is the highest-level outline. This standard is applicable to the assessment of green performance of civil buildings, including public buildings and residential buildings (MOHURD, 2019a). Out of these, education building category has been selected to demonstrate the research work, which belongs to a kind of public buildings. Although the educational buildings vary in size, normally in shape of rectangular, their characteristics make them particularly suitable for case demonstrations. Consideration will be focused on the energy-saving impact of fixed external shading design on buildings in this part of research, as well as the economic and environmental perspectives in the following chapters. A small and medium-sized educational building, which is in design stage and located in hot summer and warm winter climate of China, has been chosen as a research objective for simplifying the simulation and analysis process.

5.2.2. Fixed external shading design configurations

The common categories with respect to external window shading devices consist of horizontal shading, vertical shading, baffle-type shading, integrated shading, and louver shading (Zeng, 2018). Characteristics of common external window shading design are listed in Table 5.3.

Table 5.3 Characteristics of common external window shading devices

Category	Applicable orientation	Advantage	Disadvantage	Sample
Horizontal shading	• South direction • North direction south of the Tropic of Cancer	Large shading area, effective shading in summer and no blocking of sunlight in winter	Applicable orientation is limited	
Vertical shading	• Northeast • Northwest • North direction	Block sunlight at small altitude angles effectively	Unable to block sunlight from directly above and opposite the window	
Baffle-type shading	• From southeast to southwest	Balanced performance and outstanding artistic effect	Have a certain impact on ventilation	
Integrated shading	• Eastward • Westward	Block sunlight directly facing the window	The negative impact on sight and ventilation is serious, the lightweight movable type shading is capable to be used	
Louver shading	• Available in all directions	Improvements based on the above directions can make up for the above shortcomings to a certain extent, with flexible layout and wide application range.	Corresponding shortcomings of fixed and movable shading are existing.	

(Source: Zeng, 2018; Lin *et al*., 2020.)

As shown in Figure 3.5 and Figure 3.6, the external shading design for the studied educational building is integrated shading. The protruding length of its horizontal shading board is 500mm and the vertical shading board is 200mm (see the base case of Integrated shading A listed in Table 5.4). Simulation results from BESI showed that the energy-saving rate of building envelope regarding Integrated shading A is 5.27%. However, through intuitive experience, it is not easy to know whether the external shading design currently adopted in the studied educational building is optimal or not, or how much the maximum energy-saving effect can be achieved. In order to explore the energy-saving impact of various fixed external shading designs on buildings, the optimization of external shading board has been carried out based on four types of fixed external shading, namely horizontal shading, vertical shading, baffle-type shading, and integrated shading.

In two studies related to the optimization design of external shading for educational buildings in Guangzhou area, the range of protruding length with respect to horizontal shading has been set between 600mm and 1800mm (Liu, 2022), and the range of vertical shading has been set between 200mm and 600mm (Ge and Ren, 2021). Through further investigation with the local building structural engineer, it can be known that the commonly used protrusion length on each building façade regarding the horizontal shading board ranges from 500mm to 1000mm, the vertical shading board ranges from 200mm to 600mm, and the length of the shading baffle ranges from 500mm to 800mm. Taking into account the existing research on the protrusion length of the sunshade, the actual adopted dimension of the external sunshade, the building structural safety and facade shape, this part of research set the size range of protruding length as follow:

(1) Horizontal shading: the protruding length has been set between 500mm and 1000mm, and the step length has been set to 250mm, that is, three variable values: 500mm, 750mm, and 1000mm have been determined.
(2) Vertical shading: three variable values of 200mm, 400mm, and 600mm have been determined as the protruding length.
(3) Baffle-type shading: as the vertical baffles will affect lighting and block vision to a certain extent, the length of the vertical baffle has been determined as two variable values: 500mm and 800mm, based on the comprehensive consideration of the window height.
(4) Integrated shading: 9 shading designs have been obtained by combining the sizes of horizontal and vertical shading board (see Table 5.4). Figure 5.2 illustrated the legend of fixed

external shading designs. Corresponding 3D model and dimensions of fixed external shading cases for the studied building is illustrated in Figure 5.3 and Table 5.4.

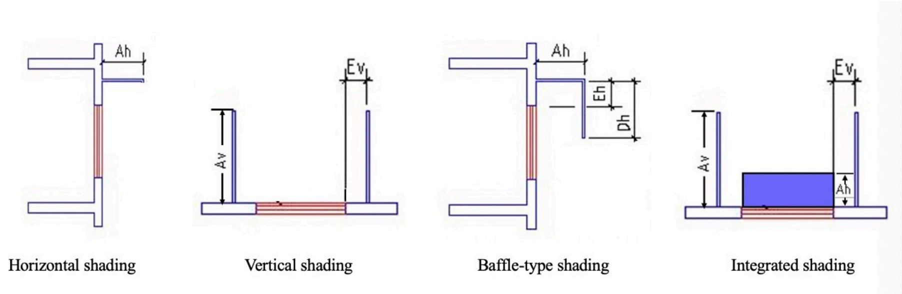


Figure 5.2 Legend of fixed external shading designs for the studied educational building

(Source: drawn by the author.)

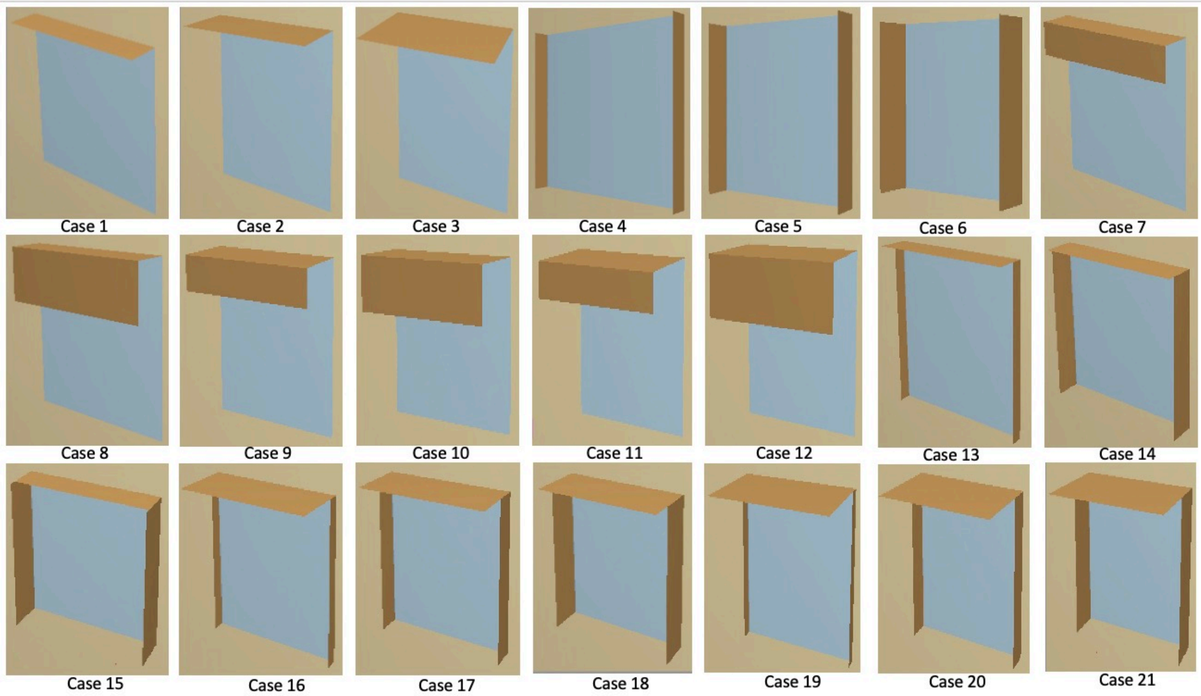


Figure 5.3 3D model of fixed external shading cases for the studied educational building

(Source: designed by the author and screenshot from BESI 2024 based on the studied educational building.)

Table 5.4 Dimensions of fixed external shading cases for the studied educational building

No.	External shading cases	Ah (mm)	Eh (mm)	Av (mm)	Ev (mm)	Dh (mm)	η*
1	Horizontal shading A	500	0	0	0	0	0
2	Horizontal shading B	750	0	0	0	0	0
3	Horizontal shading C	1000	0	0	0	0	0
4	Vertical shading A	0	0	200	0	0	0
5	Vertical shading B	0	0	400	0	0	0
6	Vertical shading C	0	0	600	0	0	0
7	Baffle-type shading A	500	0	0	0	500	0
8	Baffle-type shading B	500	0	0	0	800	0
9	Baffle-type shading C	750	0	0	0	500	0
10	Baffle-type shading D	750	0	0	0	800	0
11	Baffle-type shading E	1000	0	0	0	500	0
12	Baffle-type shading F	1000	0	0	0	800	0
13	Integrated shading A	500	0	200	0	0	0
14	Integrated shading B	500	0	400	0	0	0
15	Integrated shading C	500	0	600	0	0	0
16	Integrated shading D	750	0	200	0	0	0
17	Integrated shading E	750	0	400	0	0	0
18	Integrated shading F	750	0	600	0	0	0
19	Integrated shading G	1000	0	200	0	0	0
20	Integrated shading H	1000	0	400	0	0	0
21	Integrated shading I	1000	0	600	0	0	0

*Note: Data is derived from BESI 2024 based on the studied educational building with respect to 21 fixed external shading cases.

where Ah is the protruding length of horizontal shading board. Eh is the distance between the horizontal shading board and the upper edge of the window. Av is the protruding length of vertical shading board. Ev is the distance between the vertical shading board and the edge of the window. Dh is the length of the vertical baffle. η* is the transmittance of the baffle.

5.2.3. Simulation data input

The geographical location of Shenzhen determines the need of heat insulation in summer and unnecessary of heat preservation in winter. Since the summertime in hot summer and warm winter areas is from May to October (Zhuo, 2015), and further consultation with a local public kindergarten about the opening times throughout the year has been conducted via telephone before performing the simulation analysis. The cooling period of the studied educational building has been set from May 1st to October 31st between 8:00 am and 6:00 pm (excluding the summer vacation period from July 15th to August 25th). Shenzhen has been selected as the meteorological location, based on the meteorological data of ‘Meteorological Parameter Standard for Building Energy Saving’. Before conducting energy-saving simulation for the studied building, the parameters of various room types of the studied educational building are set (see Table 5.5), according to the provisions related to the room zoning requirement of the educational buildings in the SGPCCB-2018 (MOHURD, 2018). To maintain the reliability of simulation results, only dimension parameters of the 21 proposed shading cases (see Table 5.4) are input in the BESI system regarding the function of external shading type, other parameters of the building body are kept unchanged. This study only considers the overall energy-saving effect of a certain fixed external shading design on the studied building. Therefore, under each external shading design condition, the protrusion length of the fixed external shading board regarding each window has been set to the same size (e.g., under Horizontal shading A condition, the protrusion length of all the horizontal shading boards is set to 500mm). Due to the limited research time, the optimal protrusion length of windows in different orientations will be further improved and analyzed in the future study.

Table 5.5 Parameters setting of various types of room for the studied educational building

Type of room	**Cooling temperature (°C)**	**Heating temperature (°C)**	**Volume of fresh air**	**Personnel density**	**Lighting power density**	**Electrical appliance power density**
Fitness activity room	24°C	19°C	40(m^3/h)	4(m^2/person)	9(W/m^2)	5(W/m^2)
Kitchen	27°C	18°C	28(m^3/h)	5(m^2/person)	9(W/m^2)	5(W/m^2)
Multimedia classroom	26°C	18°C	20(m^3/h)	4(m^2/person)	9(W/m^2)	5(W/m^2)
Office	26°C	20°C	30(m^3/h)	6(m^2/person)	8(W/m^2)	5(W/m^2)
Classroom	26°C	18°C	24(m^3/h)	1.39(m^2/person)	9(W/m^2)	5(W/m^2)
Empty room	-	-	0(m^3/h)	0(m^2/person)	8(W/m^2)	0(W/m^2)

*Note: cooling period has been set from May 1st to October 31st between 8:00 am and 6:00 pm (excluding the summer vacation period from July 15th to August 25th).
Data is derived from BESI 2024 based on the studied educational building.

5.3. Results of energy-saving simulation

Based on the simulation calculation by BESI 2024, the output of analysis results regarding energy-saving rate of building envelope for the 21 proposed fixed external shading devices will be discussed based on the reference building and design building as follow:

5.3.1. Reference building

Reference building refers to a building whose thermal performance parameter of the building envelope specified in the national or industry building energy-saving design standards are selected during design process, without considering any external shading design. Through simulation calculation by BESI, the output of monthly total energy consumption for the reference building is presented in Table 5.6. It can be known that the cooling period for the reference building is May, June, July, August, September, and October. The annual comprehensive heating and cooling energy consumption for the reference building ($E_{bld.ref}$) is estimated to be 518,148.00 kWh. Table 5.7 illustrated the output of sub-item heating and cooling need for the reference building which can be obtained from BESI. Analysis results indicated that the cooling need for the reference building has been further classified into five aspects, e.g., 47,748.92 kWh for the heat transfer of the envelope structure, 120,428.10 kWh for the indoor heat gain, 11,249.00 kWh for the solar radiation heat received by windows, and 338,721.98 kWh for the fresh air/penetration.

Table 5.6 Monthly total energy consumption for the reference building

Month	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.ref}$) kWh
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	109,259	109,259
6	0	107,366	107,366
7	0	64,064	64,064
8	0	32,103	32,103
9	0	116,621	116,621
10	0	88,735	88,735
11	0	0	0
12	0	0	0
Sum	0	518,148	518,148

*Note: Data is derived from BESI 2024 based on the studied educational building.

Table 5.7 Sub-item heating and cooling need for the reference building

Classification	Heat transfer of the envelope structure	Indoor heat gain	Solar radiation heat received by windows	Fresh air/ penetration	Heat recovery	Sum
Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
Cooling need (kWh)	47,748.92	120,428.10	11,249.00	338,721.98	0.00	518,148.00

*Note: Data is derived from BESI 2024 based on the studied educational building.

5.3.2. Designed building

According to the requirements of SGPCCB-2018, the thermal performance parameters of the building envelope for the designed building should be set according to the design documents

(MOHURD, 2018). This includes different forms of fixed external shading designs. The following analysis results simply focused on the changes on the energy-saving rate of building envelope caused by the various dimension parameter setting of fixed external shading devices. There aren't any changes of other structure parameters in order to simply justify the impact of external shading design. A detailed analysis of the heating and cooling energy consumption for the designed building will be conducted from four types of fixed external shading designs, namely horizontal shading design, vertical shading design, baffle-type shading design and integrated shading design, totally 21 fixed external shading cases (see Table 5.4).

（1）Horizontal shading design

According to the dimensions of the horizontal shading design listed in Table 5.4, the protruding size of the horizontal shading board has been set to 500mm, 750mm, 1000mm, which represented 'Horizontal shading A-C'. The above shading design has been applied to all windows of the studied educational building to perform corresponding building energy consumption simulation. Similar with the calculation method for the aforementioned reference building, the monthly total energy consumption as well as sub-item heating and cooling need for the designed building regarding the three horizontal shading designs has been integrated in Table 5.8 and Table 5.9. This is based on the original analysis results generated from BESI. Table 5.8 pointed out that the cooling period of the designed building for the three horizontal shading design is May, June, July, August, September, and October, the same as the remaining external shading cases which will be discussed later.

- ❖ For horizontal shading A, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 492,311.00 kWh. Five aspects of the cooling need for the designed building are: 31,191.81 kWh for the heat transfer of the envelope structure, 119,351.84 kWh for the indoor heat gain, 4,976.85 kWh for the solar radiation heat received by windows, and 336,790.50 kWh for the fresh air/penetration.

- ❖ For horizontal shading B, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated be to 491,393.00 kWh. Five aspects of the cooling need for the designed building are: 30,662.95 kWh for the heat transfer of the envelope structure, 119,314.80 kWh for the indoor heat gain, 4,619.06 kWh for the solar radiation heat received by windows, and 336,796.20 kWh for the fresh air/penetration.

- For horizontal shading C, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 490,663.00 kWh. Five aspects of the cooling need for the designed building are: 30,298.70 kWh for the heat transfer of the envelope structure, 119,271.29 kWh for the indoor heat gain, 4,361.70 kWh for the solar radiation heat received by windows, and 336,731.31 kWh for the fresh air/penetration.

Table 5.8 Monthly total energy consumption for the designed building-Horizontal shading designs

Month	Horizontal shading A			Horizontal shading B			Horizontal shading C		
	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	104,449	104,449	0	104,325	104,325	0	104,192	104,192
6	0	102,228	102,228	0	102,003	102,003	0	101,876	101,876
7	0	60,520	60,520	0	60,439	60,439	0	60,370	60,370
8	0	30,881	30,881	0	30,731	30,731	0	30,611	30,611
9	0	110,530	110,530	0	110,363	110,363	0	110,229	110,229
10	0	83,703	83,703	0	83,532	83,532	0	83,385	83,385
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
Sum	0	492,311	492,311	0	491,393	491,393	0	490,663	490,663

*Note: Data is derived from BESI 2024 based on the studied educational building.

Table 5.9 Sub-item heating and cooling need for the designed building-Horizontal shading designs

External shading cases	Classification	Heat transfer of the envelope structure	Indoor heat gain	Solar radiation heat received by windows	Fresh air/ penetration	Heat recov ery	Sum
Horizontal shading A	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	31,191.81	119,351.84	4,976.85	336,790.50	0.00	492,311.00
Horizontal shading B	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	30,662.95	119,314.80	4,619.06	336,796.20	0.00	491,393.00
Horizontal shading C	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	30,298.70	119,271.29	4,361.70	33,6731.31	0.00	490,663.00

*Note: Data is derived from BESI 2024 based on the studied educational building.

(2) Vertical shading design

According to the dimensions of the vertical shading design listed in Table 5.4, the protruding size of the vertical shading board is set to 200mm, 400mm, 600mm, which represented ‘Vertical shading A-C’. The monthly total energy consumption as well as sub-item heating and cooling need for the designed building regarding the three vertical shading designs has been integrated in Table 5.10 and Table 5.11, based on the output analysis results generated from BESI.

- For vertical shading A, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 493,453.00 kWh. Five aspects of the cooling need for the designed building are: 32,006.50 kWh for the heat transfer of the envelope structure, 119,418.18 kWh for the indoor heat gain, 5,449.46 kWh for the solar radiation heat received by windows, and 336,578.85 kWh for the fresh air/penetration.

- For vertical shading B, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 492,175.00 kWh. Five aspects of the cooling need for the designed building are: 31,029.51 kWh for the heat transfer of the envelope structure, 119,339.23 kWh for the indoor heat gain, 5,028.39 kWh for the solar radiation heat received by windows, and 336,777.88 kWh for the fresh air/penetration.

- For vertical shading C, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 491,186.00 kWh. Five aspects of the cooling need for the designed building are: 30,445.48 kWh for the heat transfer of the envelope structure, 119,268.39 kWh for the indoor heat gain, 4,679.57 kWh for the solar radiation heat received by windows, and 336,792.57 kWh for the fresh air/penetration.

Table 5.10 Monthly total energy consumption for the designed building-Vertical shading designs

Month	Vertical shading A			Vertical shading B			Vertical shading C		
	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	104,600	104,600	0	104,418	104,418	0	104,250	104,250
6	0	102,469	102,469	0	102,185	102,185	0	101,984	101,984
7	0	60,614	60,614	0	60,495	60,495	0	60,386	60,386
8	0	31,057	31,057	0	30,870	30,870	0	30,721	30,721
9	0	110,780	110,780	0	110,530	110,530	0	110,361	110,361
10	0	83,933	83,933	0	83,677	83,677	0	83,484	83,484
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
Sum	0	493,453	493,453	0	492,175	492,175	0	491,186	491,186

*Note: Data is derived from BESI 2024 based on the studied educational building.

Table 5.11 Sub-item heating and cooling need for the designed building-Vertical shading designs

External shading cases	Classification	Heat transfer of the envelope structure	Indoor heat gain	Solar radiation heat received by windows	Fresh air/ penetration	Heat recovery	Sum
Vertical shading A	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	32,006.50	119,418.18	5,449.46	336,578.85	0.00	493,453.00
Vertical shading B	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	31,029.51	119,339.23	5,028.39	336,777.88	0.00	492,175.00
Vertical shading C	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	30,445.48	119,268.39	4,679.57	336,792.57	0.00	491,186.00

*Note: Data is derived from BESI 2024 based on the studied educational building.

(3) Baffle-type shading design

According to the dimensions of the baffle-type shading design listed in Table 5.4, the protruding size of the horizontal shading board has been set to 500mm, 750mm, 1000mm, whilst the length of the vertical baffles has been set to 500mm, 800mm, which represented 'Baffle-type shading A-F'. The monthly total energy consumption as well as sub-item heating and cooling need for the designed building regarding the six baffle-type shading designs has been translated and integrated in Table 5.12 and Table 5.13, based on the output analysis results generated from BESI.

- For baffle-type shading A, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 489,664.00 kWh. Five aspects of the cooling need for the designed building are: 29,979.48 kWh for the heat transfer of the envelope structure, 119,208.62 kWh for the indoor heat gain, 3,999.71 kWh for the solar radiation heat received by windows, and 336,476.20 kWh for the fresh air/penetration.

- For baffle-type shading B, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 487,783.00 kWh. Five aspects of the cooling need for the designed building are: 29,316.76 kWh for the heat transfer of the envelope structure, 119,059.11 kWh for the indoor heat gain, 3,422.55 kWh for the solar radiation heat received by windows, and 335,984.58 kWh for the fresh air/penetration.

- For baffle-type shading C, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 488,800.00 kWh. Five aspects of the cooling need for the designed building are: 29,699.30 kWh for the heat transfer of the envelope structure, 119,142.31 kWh for the indoor heat gain, 3,783.72 kWh for the solar radiation heat received by windows, and 336,174.67 kWh for the fresh air/penetration.

- For baffle-type shading D, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 487,302.00 kWh. Five aspects of the cooling need for the designed building are: 29,121.67 kWh for the heat transfer of the envelope structure, 119,035.08 kWh for the indoor heat gain, 3,248.85 kWh for the solar radiation heat received by windows, and 335,896.40 kWh for the fresh air/penetration.

- For baffle-type shading E, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 488,310.00 kWh. Five aspects of the cooling need for the designed building are: 29,507.30 kWh for the heat transfer of the envelope structure, 119,100.00 kWh for the indoor heat gain, 3,613.10 kWh for the solar radiation heat received by windows, and 336,089.61 kWh for the fresh air/penetration.

- For baffle-type shading F, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 487,051.00 kWh. Five aspects of the cooling need for the designed building are: 28,989.43 kWh for the heat transfer of the envelope structure, 119,031.14 kWh for the indoor heat gain, 3,137.98 kWh for the solar radiation heat received by windows, and 335,892.45 kWh for the fresh air/penetration.

Table 5.12 Monthly total energy consumption for the designed building-Baffle-type shading designs

Month	**Baffle-type shading A**			**Baffle-type shading B**			**Baffle-type shading C**		
	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	104,048	104,048	0	103,699	103,699	0	103,890	103,890
6	0	101,724	101,724	0	101,246	101,246	0	101,510	101,510
7	0	60,192	60,192	0	60,062	60,062	0	60,143	60,143
8	0	30,535	30,535	0	30,395	30,395	0	30,480	30,480
9	0	110,013	110,013	0	109,666	109,666	0	109,840	109,840
10	0	83,152	83,152	0	82,175	82,175	0	82,937	82,937
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
Sum	0	489,664	489,664	0	487,783	487,783	0	488,800	488,800

Month	**Baffle-type shading D**			**Baffle-type shading E**			**Baffle-type shading F**		
	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	103,625	103,625	0	103,784	103,784	0	103,584	103,584
6	0	101,173	101,173	0	101,383	101,383	0	101,135	101,135
7	0	60,027	60,027	0	60,106	60,106	0	60,006	60,006
8	0	30,355	30,355	0	30,436	30,436	0	30,327	30,327
9	0	109,518	109,518	0	109,757	109,757	0	109,460	109,460

10	0	82,604	82,604	0	82,844	82,844	0	82,539	82,539
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
Sum	0	487,302	487,302	0	488,310	488,310	0	487,051	487,051

*Note: Data is derived from BESI 2024 based on the studied educational building.

Table 5.13 Sub-item heating and cooling need for the designed building-Baffle-type shading designs

External shading cases	Classification	Heat transfer of the envelope structure	Indoor heat gain	Solar radiation heat received by windows	Fresh air/ penetration	Heat recovery	Sum
Baffle-type shading A	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,979.48	119,208.62	3,999.71	336,476.20	0.00	489,664.00
Baffle-type shading B	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,316.76	119,059.11	3,422.55	335,984.58	0.00	487,783.00
Baffle-type shading C	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,699.30	119,142.31	3,783.72	336,174.67	0.00	488,800.00
Baffle-type shading D	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,121.67	119,035.08	3,248.85	335,896.40	0.00	487,302.00
Baffle-type shading E	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,507.30	119,100.00	3,613.10	336,089.61	0.00	488,310.00
Baffle-type shading F	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	28,989.43	119,031.14	3,137.98	335,892.45	0.00	487,051.00

*Note: Data is derived from BESI 2024 based on the studied educational building.

(4) Integrated shading design

According to the dimensions of the integrated shading design listed in Table 5.4, the protruding size of the horizontal shading board has been set to 500mm, 750mm, 1000mm, whilst the protruding size of the vertical shading board has been set to 200mm, 400mm, 600mm, which represented ‘Integrated shading A-I’. The monthly total energy consumption as well as sub-item heating and cooling need for the designed building regarding the nine integrated shading designs has been integrated in Table 5.14 and Table 5.15, based on the output analysis results generated from BESI.

- ❖ For integrated shading A, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 490,845.00 kWh. Five aspects of the cooling need for the designed building are: 30,360.24 kWh for the heat transfer of the envelope structure, 119,268.66 kWh for the indoor heat gain, 4,444.65 kWh for the solar radiation heat received by windows, and 336,771.46 kWh for the fresh air/penetration.

- ❖ For integrated shading B, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 489,648.00 kWh. Five aspects of the cooling need for the designed building are: 29,847.16 kWh for the heat transfer of the envelope structure, 119,183.25 kWh for the indoor heat gain, 4,124.01 kWh for the solar radiation heat received by windows, and 336,493.58 kWh for the fresh air/penetration.

- ❖ For integrated shading C, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 488,461.00 kWh. Five aspects of the cooling need for the designed building are: 29,416.77 kWh for the heat transfer of the envelope structure, 119,094.97 kWh for the indoor heat gain, 3,800.54 kWh for the solar radiation heat received by windows, and 336,148.73 kWh for the fresh air/penetration.

- ❖ For integrated shading D, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 489,892.00 kWh. Five aspects of the cooling need for the designed building are: 29,983.00 kWh for the heat transfer of the envelope structure, 119,212.17 kWh for the indoor heat gain, 4,131.55 kWh for the solar radiation heat received by windows, and 336,565.28 kWh for the fresh air/penetration.

- ❖ For integrated shading E, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 488,600.00 kWh. Five aspects of the cooling need for the designed building are: 29,483.60 kWh for the heat transfer of the envelope structure, 119,119.03 kWh for the indoor heat gain, 3,803.22 kWh for the solar radiation heat received by windows, and 336,194.16 kWh for the fresh air/penetration.

- For integrated shading F, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 487,556.00 kWh. Five aspects of the cooling need for the designed building are: 29,062.22 kWh for the heat transfer of the envelope structure, 119,039.80 kWh for the indoor heat gain, 3,488.75 kWh for the solar radiation heat received by windows, and 335,965.24 kWh for the fresh air/penetration.

- For integrated shading G, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 488,984.00 kWh. Five aspects of the cooling need for the designed building are: 29,681.15 kWh for the heat transfer of the envelope structure, 119,145.53 kWh for the indoor heat gain, 3,872.50 kWh for the solar radiation heat received by windows, and 336,284.82 kWh for the fresh air/penetration.

- For integrated shading H, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 487,783.00 kWh. Five aspects of the cooling need for the designed building are: 29,204.50 kWh for the heat transfer of the envelope structure, 119,053.77 kWh for the indoor heat gain, 3,545.51 kWh for the solar radiation heat received by windows, and 335,979.23 kWh for the fresh air/penetration.

- For integrated shading I, the annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) is estimated to be 486,909.00 kWh. Five aspects of the cooling need for the designed building are: 28,777.53 kWh for the heat transfer of the envelope structure, 119,011.68 kWh for the indoor heat gain, 3,225.44 kWh for the solar radiation heat received by windows, and 335,894.36 kWh for the fresh air/penetration.

Table 5.14 Monthly total energy consumption for the designed building-Integrated shading designs

Month	Integrated shading A			Integrated shading B			Integrated shading C		
	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	104,212	104,212	0	104,008	104,008	0	103,838	103,838
6	0	101,887	101,887	0	101,678	101,678	0	101,313	101,313
7	0	60,361	60,361	0	60,274	60,274	0	60,098	60,098
8	0	30,679	30,679	0	30,529	30,529	0	30,444	30,444
9	0	110,280	110,280	0	110,015	110,015	0	109,862	109,862
10	0	83,426	83,426	0	83,144	83,144	0	82,906	82,906
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
Sum	0	490,845	490,845	0	489,648	489,648	0	488,461	488,461

Month	Integrated shading D			Integrated shading E			Integrated shading F		
	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	104,069	104,069	0	103,841	103,841	0	103,638	103,638
6	0	101,743	101,743	0	101,418	101,418	0	101,190	101,190
7	0	60,248	60,248	0	60,113	60,113	0	60,030	60,030
8	0	30,546	30,546	0	30,451	30,451	0	30,366	30,366
9	0	110,085	110,085	0	109,866	109,866	0	109,630	109,630

10	0	83,201	83,201	0	82,911	82,911	0	82,702	82,702
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
Sum	0	489,892	489,892	0	488,600	488,600	0	487,556	487,556

Month	**Integrated shading G**			**Integrated shading H**			**Integrated shading I**		
	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh	Heating energy consumption ($E_{H,bld}$) kWh	Cooling energy consumption ($E_{C,bld}$) kWh	Comprehensive heating and cooling energy consumption ($E_{bld.des}$) kWh
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	103,900	103,900	0	103,694	103,694	0	103,508	103,508
6	0	101,572	101,572	0	101,233	101,233	0	101,095	101,095
7	0	60,144	60,144	0	60,058	60,058	0	59,976	59,976
8	0	30,486	30,486	0	30,391	30,391	0	30,307	30,307
9	0	109,913	109,913	0	109,666	109,666	0	109,498	109,498
10	0	82,969	82,969	0	82,741	82,741	0	82,525	82,525
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
Sum	0	488,984	488,984	0	487,783	487,783	0	486,909	486,909

*Note: Data is derived from BESI 2024 based on the studied educational building.

Table 5.15 Sub-item heating and cooling need for the designed building-Integrated shading designs

External shading cases	Classification	Heat transfer of the envelope structure	Indoor heat gain	Solar radiation heat received by windows	Fresh air/ penetration	Heat recovery	Sum
Integrated shading A	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	30,360.24	119,268.66	4,444.65	336,771.46	0.00	490,845.00
Integrated shading B	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,847.16	119,183.25	4,124.01	336,493.58	0.00	489,648.00
Integrated shading C	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,416.77	119,094.97	3,800.54	336,148.73	0.00	488,461.00
Integrated shading D	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,983.00	119,212.17	4,131.55	336,565.28	0.00	489,892.00
Integrated shading E	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,483.60	119,119.03	3,803.22	336,194.16	0.00	488,600.00
Integrated shading F	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,062.22	119,039.80	3,488.75	335,965.24	0.00	487,556.00
Integrated shading G	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,681.15	119,145.53	3,872.50	336,284.82	0.00	488,984.00
Integrated shading H	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	29,204.50	119,053.77	3,545.51	335,979.23	0.00	487,783.00
Integrated shading I	Heating need (kWh)	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling need (kWh)	28,777.53	119,011.68	3,225.44	335,894.36	0.00	486,909.00

*Note: Data is derived from BESI 2024 based on the studied educational building.

5.4. Discussion and implications

According to the equation (5.1), the energy-saving rate of building envelope (Φ_{ENV}) regarding the 21 proposed fixed external shading devices can be calculated. The corresponding estimated value of annual comprehensive heating and cooling energy consumption for reference building ($E_{bld,ref}$) and designed building ($E_{bld,des}$) with respect to the 21 cases are collected from Table 5.6, Table 5.8, Table 5.10, Table 5.12, Table 5.14. The calculation results regarding the values of energy-saving rate of building envelope with respect to 21 shading cases are organized in Table 5.16. Detailed analysis for each shading type is discussed as follow:

Table 5.16 Energy-saving rate of building envelope regarding 21 shading cases for the studied educational building

No.	Fixed external shading cases	$E_{bld.ref}$ (kWh)	$E_{bld.des}$ (kWh)	Φ_{ENV}
1	Horizontal shading A	518,148	492,311	4.99%
2	Horizontal shading B	518,148	491,393	5.16%
3	Horizontal shading C	518,148	490,663	5.30%
4	Vertical shading A	518,148	493,453	4.77%
5	Vertical shading B	518,148	492,175	5.01%
6	Vertical shading C	518,148	491,186	5.20%
7	Baffle-type shading A	518,148	489,664	5.50%
8	Baffle-type shading B	518,148	487,783	5.86%
9	Baffle-type shading C	518,148	488,800	5.66%
10	Baffle-type shading D	518,148	487,302	5.95%
11	Baffle-type shading E	518,148	488,310	5.76%
12	Baffle-type shading F	518,148	487,051	6.00%
13	Integrated shading A	518,148	490,845	5.27%
14	Integrated shading B	518,148	489,648	5.50%
15	Integrated shading C	518,148	488,461	5.73%
16	Integrated shading D	518,148	489,892	5.45%
17	Integrated shading E	518,148	488,600	5.70%
18	Integrated shading F	518,148	487,556	5.90%
19	Integrated shading G	518,148	488,984	5.63%
20	Integrated shading H	518,148	487,783	5.86%
21	Integrated shading I	518,148	486,909	6.03%

5.4.1. Horizontal shading design

As illustrated in Figure 5.4, the protruding size of horizontal shading designs ranges from 500mm to 1000mm. As the horizontal protruding length increases, the building's annual comprehensive heating and cooling energy consumption shows a downward trend. When the horizontal protruding length reaches 1000mm, $E_{bld.des}$ reduces to the minimum value. On the contrary, as the horizontal protruding length increases, the energy-saving rate of building envelope shows an upward trend (see Figure 5.5). When the horizontal protruding length reaches 1000mm, Φ_{ENV} increases to the maximum value, equivalent to an increase of 0.062%

in energy-saving rate of building envelope for every 100mm increase in horizontal protrusion length. Hence, in the process of selecting suitable horizontal protruding size for horizontal shading design, if only consider the building energy consumption and the energy-saving rate of building envelope, 1000mm is an optimum choice in this specific case, to ensure the lowest heating and cooling energy consumption and the highest energy-saving rate of building envelope.

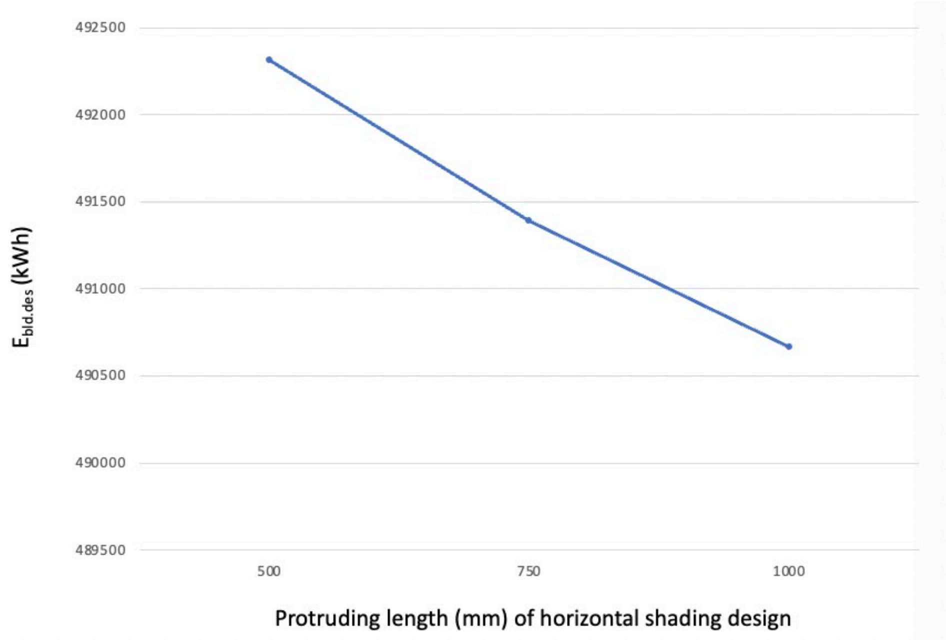


Figure 5.4 Annual comprehensive heating and cooling energy consumption for designed building ($E_{bld.des}$) with respect to horizontal shading design

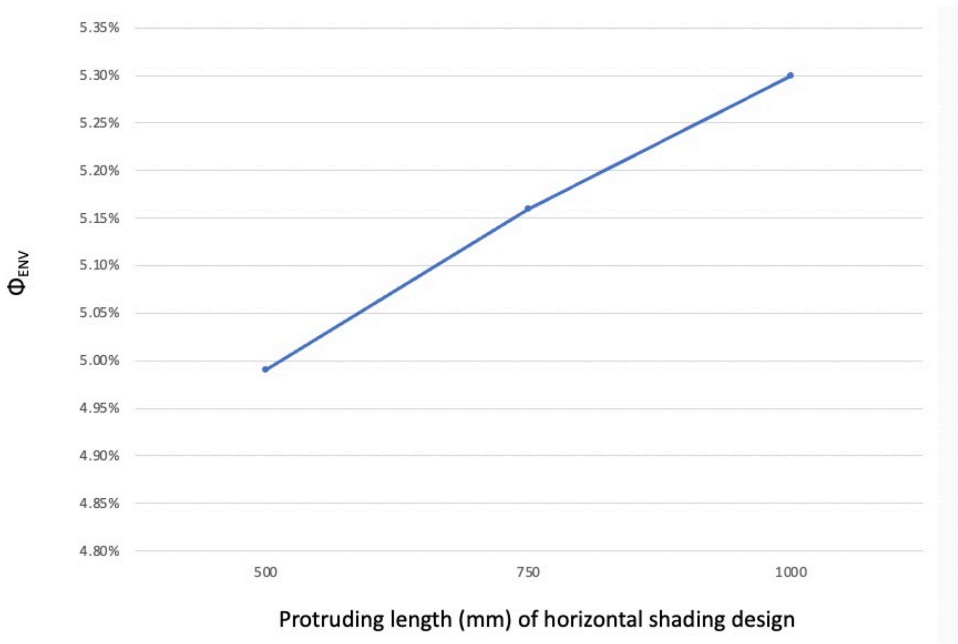


Figure 5.5 Energy-saving rate of building envelope for the designed building (Φ_{ENV}) with respect to horizontal shading design

5.4.2. Vertical shading design

As illustrated in Figure 5.6, the protruding size of vertical shading designs ranges from 200mm to 600mm. As the vertical protruding length increases, the building's annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) shows a downward trend. When the vertical protruding length reaches 600mm, $E_{bld.des}$ reduces to the minimum value. On the contrary, as the vertical protruding length increases, the energy-saving rate of building envelope (Φ_{ENV}) shows an upward trend (see Figure 5.7). When the vertical protruding length reaches 600mm, Φ_{ENV} increases to the maximum value, equivalent to an increase of 0.11% in energy-saving rate of building envelope for every 100mm increase in vertical protrusion length. Hence, in the process of selecting suitable vertical protruding size for vertical shading design, if only consider the building energy consumption and the energy-saving rate of building envelope, 600mm is an optimum choice in this specific case, to ensure the lowest heating and cooling energy consumption and the highest energy-saving rate of building envelope.

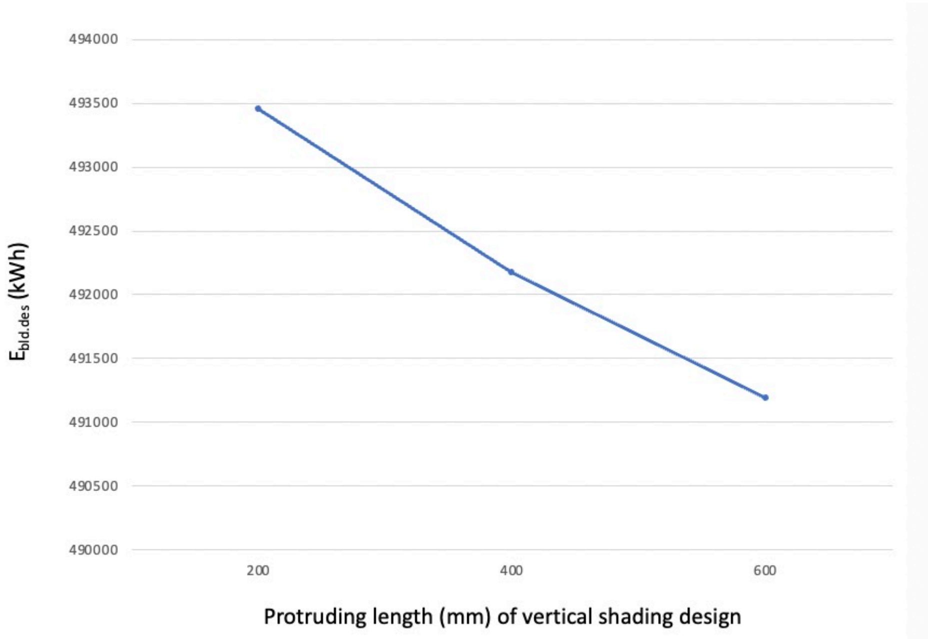


Figure 5.6 Annual comprehensive heating and cooling energy consumption for designed building ($E_{bld.des}$) with respect to vertical shading design

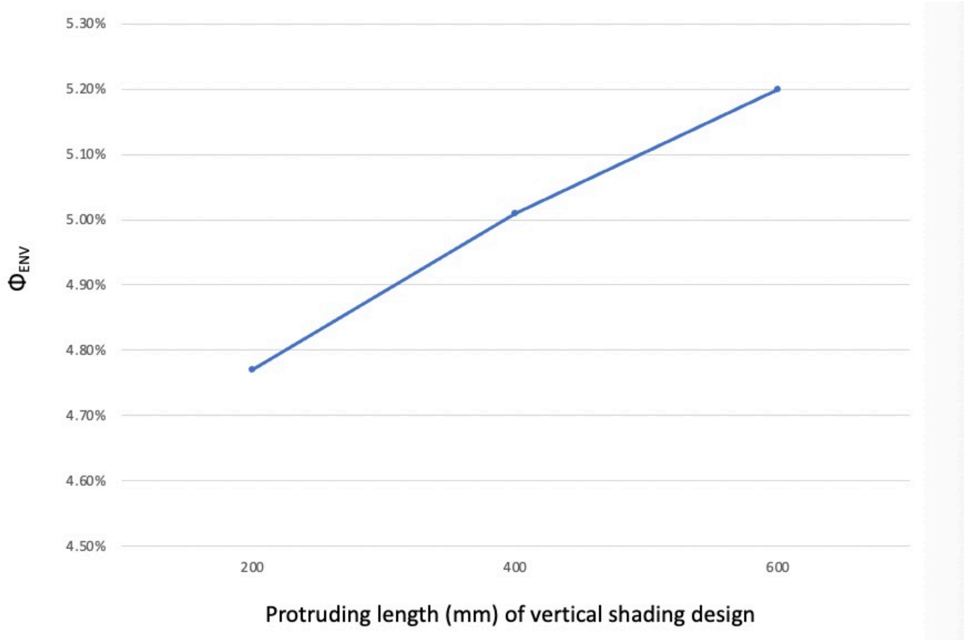


Figure 5.7 Energy-saving rate of building envelope for the designed building (Φ_{ENV}) with respect to vertical shading design

5.4.3. Baffle-type shading design

As listed in Table 5.17, the protruding size of horizontal shading board ranges from 500mm to 1000mm, whilst the length of vertical baffle ranges from 500mm to 800mm. When the horizontal protrusion size is constant, the value of building's annual comprehensive heating and cooling energy consumption ($E_{bld.des}$) decreases as the length of the vertical baffle increases, while the value of energy-saving rate of building envelope (Φ_{ENV}) increases.

When the length of the vertical baffle is constant, the value of annual heating and cooling energy consumption ($E_{bld.des}$) decreases as the horizontal protruding size increases, while the value of energy-saving rate of building envelope (Φ_{ENV}) increases. Therefore, in the process of selecting the suitable size of the baffle-type shading design, if only consider the values of building heating and cooling energy consumption or the energy-saving rate of building envelope, the maximum length of the horizontal shading board and the vertical baffle must be taken into account. The optimum baffle-type shading design is the case with horizontal protruding length of 1000mm and vertical baffle length of 800mm. This is to minimize the building's heating and cooling energy consumption or maximize the energy-saving rate of building envelope.

Table 5.17 Energy-saving effects regarding baffle-type shading design for the designed building

Fixed external shading cases	Horizontal protruding length (mm)	Vertical baffle length (mm)	$E_{bld.des}$ (kWh)	Φ_{ENV}
Baffle-type shading A	500	500	489,664	5.50%
Baffle-type shading B		800	487,783	5.86%
Baffle-type shading C	750	500	488,800	5.66%
Baffle-type shading D		800	487,302	5.95%
Baffle-type shading E	1000	500	488,310	5.76%
Baffle-type shading F		800	487,051	6.00%

5.4.4. Integrated shading design

As listed in Table 5.18, the protruding size of horizontal shading board ranges from 500mm to 1000mm, whilst the protruding size of vertical shading board ranges from 200mm to 600mm.When the horizontal protruding size is constant, the value of building's annual heating and cooling energy consumption ($E_{bld.des}$) decreases as the protruding size of vertical shading increases, while the energy-saving rate of building envelope (Φ_{ENV}) increases.

When the protruding size of the vertical shading is constant, the annual heating and cooling energy consumption ($E_{bld.des}$) decreases as the protruding size of the horizontal shading board increases, while the energy-saving rate of building envelope (Φ_{ENV}) increases. Therefore, in the process of selecting the optimum protruding size of the integrated shading design, if only the building heating and cooling energy consumption or the energy saving-rate of building envelope is considered, the maximum protruding length of the horizontal and vertical shading board should be selected. That is, the optimum integrated shading design is the case with a horizontal protruding length of 1000mm and a vertical protruding length of 600mm in this case, so as to minimize the building energy consumption or maximize the energy-saving rate of building envelope.

Table 5.18 Energy-saving effects regarding integrated shading design for the designed building

Fixed external shading cases	Horizontal protruding length (mm)	Vertical protruding length (mm)	$E_{bld.des}$ (kWh)	Φ_{ENV}
Integrated shading A	500	200	490,845	5.27%
Integrated shading B		400	489,648	5.50%
Integrated shading C		600	488,461	5.73%
Integrated shading D	750	200	489,892	5.45%
Integrated shading E		400	488,600	5.70%
Integrated shading F		600	487,556	5.90%
Integrated shading G	1000	200	488,984	5.63%
Integrated shading H		400	487,783	5.86%
Integrated shading I		600	486,909	6.03%

It can be known from the analysis results listed in Table 5.16 that, among the 21 proposed fixed external shading designs, the Integrated shading I has the best energy-saving effect, of which protruding size of horizontal shading board is 1000mm and vertical shading board is 600mm. The annual heating and cooling energy consumption of this optimum shading case is 486,909kWh, and the value of energy-saving rate of building envelope is 6.03%, 12.6% higher than the base external shading case named Integrated shading A.

5.5. Summary

This chapter presents a case study to demonstrate the application of a Chinese local building energy simulation system named BESI 2024 in a typical design activity. It examined 21 fixed external shading devices planned for a three-storey educational building framed in structural steel, which is a One-star certified green kindergarten project. This is to generate an optimum shading option from energy saving perspective among four shading types (e.g., horizontal shading, vertical shading, baffle-type shading, and integrated shading). Through calculation of the percentage by which the annual heating and cooling energy consumption of designed building is reduced compared to the reference building, the assessed criteria named energy-saving rate of building envelop (Φ_{ENV}) regarding each shading case has been generated. This is based on the changes of the dimensions with respect to the shading options. Simulation results reveals that the optimum shading option with the best energy-saving impact on buildings is Integrated shading I in this specific case, of which protruding size of horizontal shading board is 1000mm and vertical shading board is 600mm. The annual heating and cooling energy consumption of this optimum shading case is 486,909 kWh, and its energy-saving rate of building envelope is 6.03%, 12.6% higher than the base external shading case of Integrated shading A.

The energy-saving rate of building envelope is mainly related to the design of the external shading, the protruding length of the shading boards and the length of the shading baffle. Various energy-saving effects will be generated by different types of external shading designs. In the same type of fixed external shading devices, the energy-saving rate of building envelope is directly proportional to the protruding length of the sunshade and the length of the baffle. Further analytical results indicate that there will be an increase of 0.062% in energy-saving rate of building envelope for every 100mm increase in horizontal protrusion length regarding the horizontal external shading design, whilst an increase of 0.11% in energy-saving rate of the building envelope for every 100mm increase in vertical protrusion length with respect to the vertical external shading design. Moreover, this specific result is to apply a prototype of case study as an evidence of efficacy for the subsequent economic, environmental, and multi-criteria assessment in the following chapters.

Chapter 6. Initial Investment Assessment

In this chapter, the use of proposed LCCA method is demonstrated for the proposed fixed external shading designs in the studied green educational building in Shenzhen. The intention is to assess the initial investment regarding six fixed external shading devices for subsequent comprehensive multi-criteria evaluation. Several methods have been used, such as LCCA, building power consumption simulation by CEEB 2024 and PV calculation. A comparative study has been adopted for analyzing the PV of costs at different life cycle stages regarding the shading devices. An investigation of the external shading products on sale, a detailed LCC assessment process and corresponding assessment results are discussed in this chapter.

6.1. Investigation of external shading products on sale in Chinese market

Among the energy-efficiency design of green buildings, appropriate shading design can help improve the energy-saving effect of the building. Through a series of market research, it has been found that there are currently a wide variety of external shading products on sale. Feedback from the preliminary investigation with respondent A and C point out that the fixed external shading devices are the most adopted shading design in the context of China. And the low investment cost is the primary factor that decision-makers consider when choosing a certain shading component. This can be further inferred that the LCC, and the future benefits of the shading components would bring to saving of building energy consumption which has been overlooked, let alone their initial investment from the perspective of LCCA or the implementation in a green building assessment practice have been considered. To further explore the external shading products currently on sale in the Chinese market, investigation has been conducted with the sale managers in 10 main Chinese manufacturers of external shading products respectively (see Table 6.1), most of which are located in the cities of hot summer and warm winter climate region. Due to the requirement of privacy protection, the information of manufacturers listed below has been anonymized.

Table 6.1 10 main Chinese local manufacturers of external shading products

Manufacturer	Location	Main external shading products on sale
Manufacturer A	High-tech Industrial Technology Development District of Guangzhou	External louver, external roller blind
Manufacturer B	Baiyun District of Guangzhou	External roller blind
Manufacturer C	Huangpu District of Guangzhou	Hollow glass, external venetian blind, external roller blind, aluminum external louver
Manufacturer D	Zengcheng District of Guangzhou	Concrete shading board
Manufacturer E	Baiyun District of Guangzhou	Fusiform louver, hollow louver, single panel perforated louver, glass louver
Manufacturer F	Xiqing District of Guangzhou	Fusiform louver, flat louver, external roller blind
Manufacturer G	Fenggang District of Guangzhou	External roller blind
Manufacturer H	Panyu District of Guangzhou	External roller blind
Manufacturer I	City of Changsha	External louver
Manufacturer J	Chaoyang District of Beijing	External louver, external roller blind, shading board

It can be known from the investigation with the local external shading product manufacturers that the products available on the Chinese market are mainly in type of adjustable shading, which have higher costs than the fixed ones. Since the fixed external shading design are being considered in this research project, feedbacks from the above investigation with the product manufacturers seem irrelevant to subsequent research. Meanwhile, simulation results in the last chapter showed that materials of shading components were not the factors to be considered when conducting simulation by BESI 2024 for obtaining the values of energy-saving rate of building envelope. However, from an economic perspective, the investment costs of external shading components vary from different shading materials. Differences in material properties not only affect the life cycle of the shading components, but also influence their maintenance and replacement frequency, resulting in various costs and their corresponding PV. Hence, further investigation in selecting appropriate shading materials is continuing with relevant manufacturers.

6.2. The assessment process of fixed external shading devices

6.2.1. Selection of fixed external shading devices

Determination of the investigated fixed external shading alternatives is discussed from the perspective of dimension and materials regarding the shading components in this section.

(1) Dimension selection

Simulation results in the last chapter showed that the optimum fixed external shading design with best energy-saving impact on the studied green educational building is 'Integrated shading I'. This protruding size of horizontal shading board is 1000mm and vertical shading board is 600mm, with 6.03% energy-saving rate of building envelope. The optimum (Integrated shading I) and the base external shading case (Integrated shading A) are selected in this part of research to form the targeted fixed external shading strategies. Dimension of the above two cases is given in Table 6.2:

Table 6.2 Dimension of two studied fixed external shading cases

External shading case		**Protruding size of horizontal shading board (mm)**	**Protruding size of vertical shading board (mm)**	**Energy-saving rate of building envelope**
Base case	Integrated shading A	500	200	5.27%
Optimum case	Integrated shading I	1000	600	6.03%

(2) Material selection

Through further investigation with Manufacturer D, whose main shading products are concrete shading board, it can be noted that the materials commonly used to make fixed external shading components are concrete panel, wood, metal, and plastic. Considering the load-bearing effect of the external shading components, the weight of the concrete one is much heavier than those of the other three materials when making a same size shading board. During the installation and fixing process of an external shading component, issues such as falling or cracking due to overweight for the concrete material may appear. Therefore, the other three categories of materials (wood, metal, and plastic), have been selected for subsequent economic analysis. To figure out the representative materials and their characteristics of the above three categories, investigation has been conducted with over 50 material suppliers which located in the Pearl River Delta region of China. This combines the document survey of the product brochures provided by the suppliers. Feedback from the above investigation indicate that Merbau, Aluminum, and Polycarbonate are the three representative materials that can be selected for subsequent analysis. Characteristics of the three targeted shading materials are given in Table 6.3, which have better adaption to the hot-humid climate environment in southern part of China.

Table 6.3 Characteristics of the shading materials

Material category	Representative materials	Materials characteristics
Wood	Merbau	In wood category, merbau imported from Indonesia has better performance of anti-corrosion and moisture resistance, which has a higher hardness than other wood species and can be used in outdoor environments for a long time.
Metal	Aluminum	In metal category, aluminum is light in weight, with good performance of rigidity, acid, and alkali resistance.
Plastic	Polycarbonate (Dark color)	In plastic category, polycarbonate is about 300 times harder than tempered glass, with a strong performance of flame retardancy, temperature resistance, and UV-rays protection.

(3) Determination of fixed external shading strategies

Two shading dimensions and three shading materials listed in Table 6.2 and Table 6.3 are selected to form the six fixed external shading alternatives (see Figure 6.1).

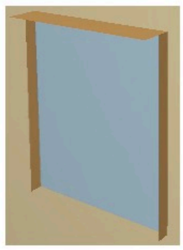
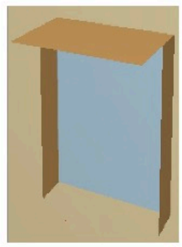
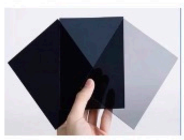
	External shading strategy A	External shading strategy B	
 Merbau	 Integrated shading A (500mm, 200mm)	 Integrated shading I (1000mm,600mm)	Merbau A
			Merbau B
 Aluminum			Aluminum A
			Aluminum B
 Polycarbonate			Polycarbonate A
			Polycarbonate B

Figure 6.1 Six fixed external shading alternatives to be studied by LCCA

6.2.2. Life cycle cost analysis

The process of LCCA is discussed in terms of analysis framework, cost data collection, PV calculation in this section.

(1) Framework of LCCA

A LCCA framework of fixed external shading strategies has been delivered according to the feedback from the investigation with materials suppliers (see Figure 6.2). Four main life cycle stages for the external shading devices include: construction, installation, operation & maintenance (O&M), and disposal (also known as demolition). The aggregated costs from the four life cycle stages determine the LCC of fixed external shading devices, as a considered criteria for subsequent multi-criteria assessment. As shown in Figure 6.2, construction stage refers to the acquirement of the external shading components, including the purchase and processing materials. The installation stage mainly includes the transportation of external shading components from the material suppliers' warehouse to a construction project site, as well as on-site installation. O&M stage comprises the utility expenditure occurred during the operation of building after equipping with the fixed external shading devices. Meanwhile, the process of maintaining the components by one-off replacement according to the lifespan of materials are also considered, including regular protective paint coating. Disposal happens at the end of components' lifespan when the external shading devices have been dismantled and transported to the landfill or the renewable resource recycling center. All the aforementioned materials and processes need capital investments (Huang *et al*., 2019).

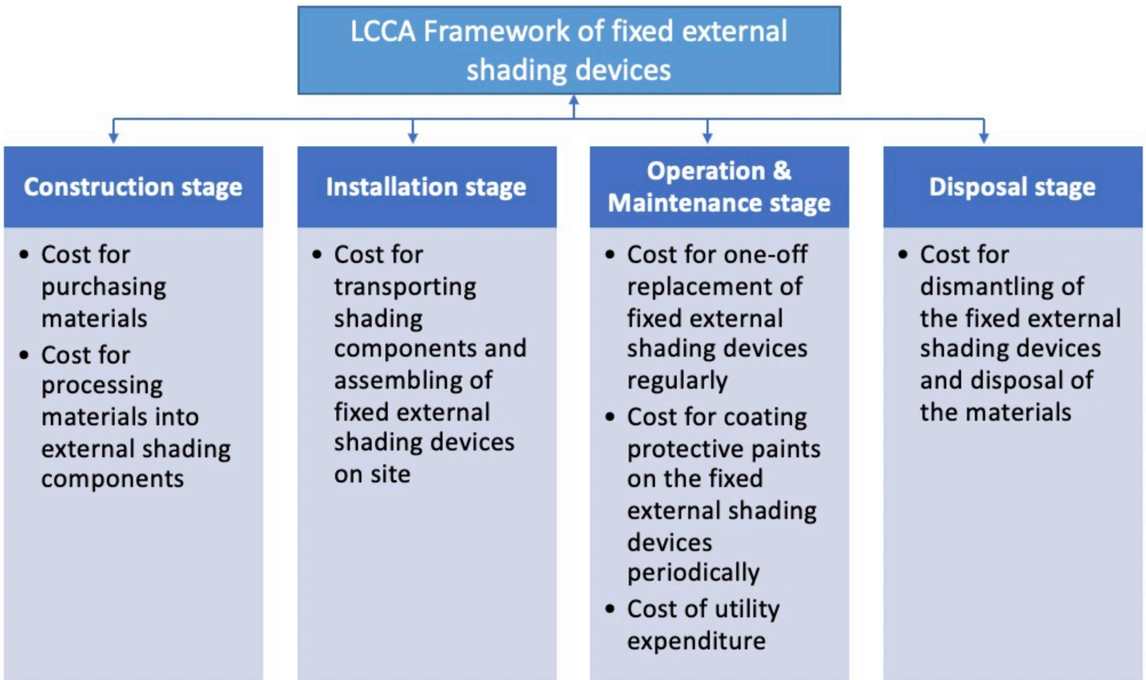


Figure 6.2 Framework of life cycle cost analysis (LCCA) of fixed external shading devices

(2) Cost data collection

Through further investigation with material suppliers, the Merbau can be cut into any thickness, the fluorocarbon coated Aluminum can be made into a thickness of 1mm-10mm, and the Polycarbonate can be made into a thickness of 1mm-10mm. Here, the median of thickness for the above three materials is taken as 5mm. According to the windows parameters of the studied educational building listed in Table 3.3 and the protruding length of external shading components for Integrated shading A and Integrated shading I listed in Table 5.9, the dimensions and quantity of the external shading components with respect to strategy A and B are given in Table 6.4.

Table 6.4 Attributes of the fixed external shading devices for the two studied external shading strategies

External shading strategy	Length (m)	Width (m)	Thickness (m)	Quantity	Surface area (m^2)	Volume (m^3)
External shading strategy A (500mm, 200mm)	1.640	0.500	0.005	29	48.181	0.119
	2.600	0.500	0.005	5	13.155	0.033
	1.000	0.500	0.005	9	9.135	0.023
	3.100	0.500	0.005	3	9.408	0.023
	2.310	0.500	0.005	15	35.072	0.087
	2.500	0.200	0.005	122	125.294	0.305
Sum					**240.244**	**0.589**
External shading strategy B (1000mm, 600mm)	1.640	1.000	0.005	29	95.886	0.238
	2.600	1.000	0.005	5	26.180	0.065
	1.000	1.000	0.005	9	18.180	0.045
	3.100	1.000	0.005	3	18.723	0.047
	2.310	1.000	0.005	15	69.797	0.173
	2.500	0.600	0.005	122	369.782	0.915
Sum					**598.547**	**1.483**

Material parameters and corresponding cost data have been collected through investigation with local material suppliers and renewable resource recycling companies. Material category, density, lifespan, surface area, volume, weights, price of materials and coatings, material recycling price, energy-saving rate of building envelope regarding six shading alternatives are given in Table 6.5. As for lifespan, the life cycle of Merbau ranges from 30-50 years, Aluminum ranges from 10-20 years, and Polycarbonate ranges from 5-10 years. Here, the median values of lifespan for the above three materials are taken as 40, 15 and 7.5 years respectively. As for the total area and total volume of shading devices and coatings, they are calculated by their respective dimensions. It has been found from the investigation that the unit price of Merbau ranges from £1,028.14-£1,060.61 per m^3, Aluminum ranges from £48.70-£51.95 per m^2, Polycarbonate ranges from £9.74-£10.28 per m^2. The median values of unit price for the above three materials are taken as £1,044.37, £50.32, and £10.01 respectively. The water-based coatings are £1.24 per m^2, and the fluorocarbon coatings are £3.25 per m^2. The recycling unit price of Merbau is £0.01 per kg, Aluminum ranges from £1.620-£2.168 per kg, Polycarbonate ranges from £1.080-£2.166 per kg. The median value of unit price for the latter two materials are taken as £1.894 and £1.623 respectively.

(3) Present value of LCC

A rational comparison of running costs among six selected external shading alternatives has been conducted based on their cost data. During the study period of a certain product, economic performance was an independent assessment of the product's operating costs using LCCA method (Babaizadeh *et al*., 2015). This study period normally begins with the purchase and installation of the external shading components and ends at a fixed date in the future when the component's life cycle ended. In LCCA method of this research, the time value of money is calculated by considering a discount rate announced by Bank of China recently. The future costs have been converted to their corresponding PV based on a 5.04% discount rate (BOC, 2024). All the costs listed in Table 6.5 have been escalated at an inflation rate of 2.5% (BOC, 2024), and converted from RMB to GBP at the exchange rate of 1:9.24 (This is also applied to the subsequent analysis) (Alipay, 2024). Considering the location of studied educational building and the cost control of material transportation, the unit prices of the six aforementioned external shading alternatives, including processing and transportation costs, have been collected through investigation with several material suppliers in Shenzhen, whose projects are of various types of buildings and outdoor facilities in southern China. The residual values of the external shading components have been collected by consulting the recycling prices with several renewable resource recycling companies in Shenzhen. The PV of future money during each life cycle stage can be calculated by equation (6.1) (Tushar *et al*., 2022):

$$PV = FV \times \frac{1}{(1+i)^n} \tag{6.1}$$

where PV is the present value of money, FV is the future sum of money, i is the discount rate, n is the lifespan of the external shading materials.

The total LCC of the fixed external shading devices is the sum of the present value of costs in all life cycle stages, which can be represented in equation (6.2) (Huang et al., 2019):

$$LCC = C_{Con} + C_{Ins} + C_{O\&M} + C_{Dis} \tag{6.2}$$

where LCC is the life cycle cost of fixed external shading devices in present value (PV).

C_{Con} is the PV of construction cost.

C_{Ins} is the PV of installation cost.

$C_{O\&M}$ is the PV of operation and maintenance cost.

C_{Dis} is the PV of disposal cost.

Table 6.5 Profile information of the selected fixed external shading alternatives

	Merbau A	**Merbau B**	**Aluminum A**	**Aluminum B**	**Polycarbonate A**	**Polycarbonate B**
Location	outdoor	outdoor	outdoor	outdoor	outdoor	outdoor
Material category	Wood	Wood	Metal	Metal	Plastic	Plastic
Density of materials (kg/m^3)	1,000	1,000	2,720	2,720	1,200	1,200
Density of coatings (kg/m^3)	1,150	1,150	1,500	1,500	-	-
Lifespan (year)	40	40	15	15	7.5	7.5
Surface area of shading devices (m^2)	240.244	598.547	240.244	598.547	240.244	598.547
Volume of shading devices (m^3)	0.589	1.483	0.589	1.483	0.589	1.483
Volume of coatings (m^3)	0.0418	0.1041	0.032	0.0798	-	-
Weights of shading devices (kg)	589	1,483	1,602.080	4,033.760	706.800	1,779.600
Weights of coatings (kg)	48.049	119.709	48.049	119.709	-	-
Price of materials per unit	£1,044.37 per m^3	£1,044.37 per m^3	£50.32 per m^2	£50.32 per m^2	£10.01 per m^2	£10.01per m^2
Price of coatings per unit	£1.24 per m^2	£1.24 per m^2	£3.25 per m^2	£3.25 per m^2	-	-
Recycling price per unit	£0.01 per kg	£0.01 per kg	£1.894 per kg	£1.894 per kg	£1.623 per kg	£1.623 per kg
Energy-saving rate of building envelope	5.27%	6.03%	5.27%	6.03%	5.27%	6.03%

(Source: material suppliers and renewable resource recycling companies in Shenzhen.)

6.2.3. Electricity expenditure estimation

The adoption of CEEB 2024 and assessment criteria determination are discussed in this section.

(1) CEEB 2024

As stated previously, building energy consumption changed with the design of external shading. However, feedback from the investigation with respondent D points out that the energy-saving rate of building envelope which generated by using BESI 2024 simulation in Chapter 5 does not affect the electricity bills of building. However, the annual comprehensive power consumption occurred during the building operation will have an impact on the utility expenditure (see Figure 6.2). This can be estimated through simulation by CEEB 2024, a building carbon emission simulation software based on GBSWARE platform. Simulation results can be used for supporting initial data collection during the building operation stage. Subsequent analysis will focus on the changes in building power consumption caused by the replacement of six fixed external shading alternatives, thereby estimating the corresponding electricity expenditure.

(2) Determination of assessment criteria

The potential savings of electricity expenditure achieved by the installation of fixed external shading devices is the focus in this part of research. As stated previously, the corresponding annual power consumption has been calculated by CEEB 2024 (see formula 5.2). Subsequently, through comparing the annual power consumption of the reference building and the designed building based on a certain shading case, the difference between the above two values, otherwise known as the savings of power consumption (ΔE), has been estimated. Similar to the calculation of the energy-saving rate of building envelope in Chapter 5, the following analysis simply focus on the changes on the building power consumption resulting from the setting of external shading dimension parameters. This does not consider other changes of structure parameters owing to the simple demonstration regarding the impact of external shading design. The value of power consumption savings (ΔE) can be estimated by the equation (6.3):

$$\Delta E = E_{sum,ref} - E_{sum,des} \tag{6.3}$$

where ΔE is the difference value of annual comprehensive power consumption between the reference building and the designed building (kWh/year).

$E_{sum,ref}$ is the annual comprehensive power consumption of the reference building (kWh/year). $E_{sum,des}$ is the annual comprehensive power consumption of the designed building (kWh/year).

To estimate the potential savings of electricity expenditure for a certain external shading case, data of electricity price in Shenzhen has been collected. According to the provisions of the 'Notice of the Guangdong Provincial Development and Reform Commission on Adjusting Sales Prices and Other Relevant Issues' (Guangdong Development and Reform Commission [2017] No. 498), a stepped pricing method of domestic power consumption has been applied in Shenzhen, ranging from £0.071-£0.104 kWh (see Table 6.6) (Shenzhen China, 2024). To simplify the calculation, the power unit price in this study has taken a median value of £0.088 kWh.

Table 6.6 List of residential power price in Shenzhen

	Classification of power usage	**Unit price (£/kWh)**
Stepped price of power consumption	First level (0-260kWh in summer, 0-200kWh in other seasons)	0.071
	Second level (261-600kWh in summer, 201-400kWh in other seasons)	0.077
	Third level (Above 600kWh in summer, above 400kWh in other seasons)	0.104

(Source: Shenzhen China, 2024.)

(3) Simulation data input

Since the calculation of power consumption during the building operation stage belongs to part of the carbon emission simulation analysis, the involved parameters of cooling, lighting, building material usage, and carbon emission factors are required to be input in one go before performing the carbon emission simulation in CEEB 2024. However, the following analysis in this chapter only focuses on the power consumption owing to the operation of the cooling and lighting systems, as they are the most relevant data for electricity expenditure calculation. The remaining parameters related to carbon emission that have been set will be further discussed in Chapter 7 regarding environment perspective. According to the requirement of energy efficiency rating indexes with respect to single-cooling room air conditioning regulators, which have been specified in the 'Minimum allowable values of the energy efficiency and energy efficiency grades for room air conditioners GB 21455-2019' (SAMR and SA, 2019), the parameters of the cooling and lighting systems are set as follows (see Table 6.7).

Table 6.7 Parameter settings of the cooling and lighting system for the studied kindergarten project

Type of cooling system	First-level energy efficiency unit room air conditioner
Coefficient of performance (COP)	5.8
Coverage area (m^2)	1,655.87
Power consumption per unit air volume for new fan ($W/(m^3/h)$)	0.24
Power consumption per unit air volume for exhaust fan ($W/(m^3/h)$)	0.24
Lighting power density (W/m^2)	9

6.3. Analysis of the assessment results

It is expected that the cooling energy consumption and power consumption during building operation stage, CO_2 emissions, the initial cost, operation cost, maintenance cost and residual value would be influenced by either shading materials or the dimension of shading components. This part of the research focuses on the economic impact of six different fixed external shading devices regarding their whole life cycle. Detailed analysis and assessment results regarding the PV of the costs involved in the stages of construction, installation, O&M, and disposal of the fixed external shading devices will be given in this section. Hence, the NPV of the LCC regarding each external shading alternative can be derived.

6.3.1. Construction cost

Feedback from the material suppliers indicates that the construction cost of the fixed external shading devices consisting of purchasing and processing materials, the sum of which is the provided unit price. However, due to the difficulty to obtain the detailed cost data from the suppliers, construction costs can hardly be further broken down. Listed in Table 6.5, the weights of the forementioned three materials have been calculated by multiplying the volume by their density. As a part of material processing, suppliers indicates that the water-based coatings need to be coated covering the surface of Merbau before installation and each year after installation. This is to maintain their color and improve waterproof performance. In addition, the fluorocarbon coatings need to be applied once after the Aluminum components have been made, to protect the color of materials and improve their anti-rust, anti-corrosion, and anti-oxidation performance. Investigation shows that each square meter of surface area regarding Merbau or Aluminum requires 0.2kg of protective coatings, estimating that the weights of the above two coatings are 48.049kg and 119.709kg one-off. The costs of materials and coatings have been estimated by multiplying their unit prices by the volume or surface area of the six fixed external shading devices (see Table 6.8). The top three external shading designs with highest construction costs are Aluminum B, Aluminum A and Polycarbonate B.

Table 6.8 Construction cost of the six proposed fixed external shading devices

Construction costs elements	Cost (£)					
	Merbau A	Merbau B	Aluminum A	Aluminum B	Polycarbonate A	Polycarbonate B
Material	615.13	1,548.80	12,089.08	30,118.89	2,404.84	5,991.46
Coatings	297.90	742.20	780.79	1,945.28	-	-
Total construction cost	**913.03**	**2,291.00**	**12,869.87**	**32,064.17**	**2,404.84**	**5,991.46**

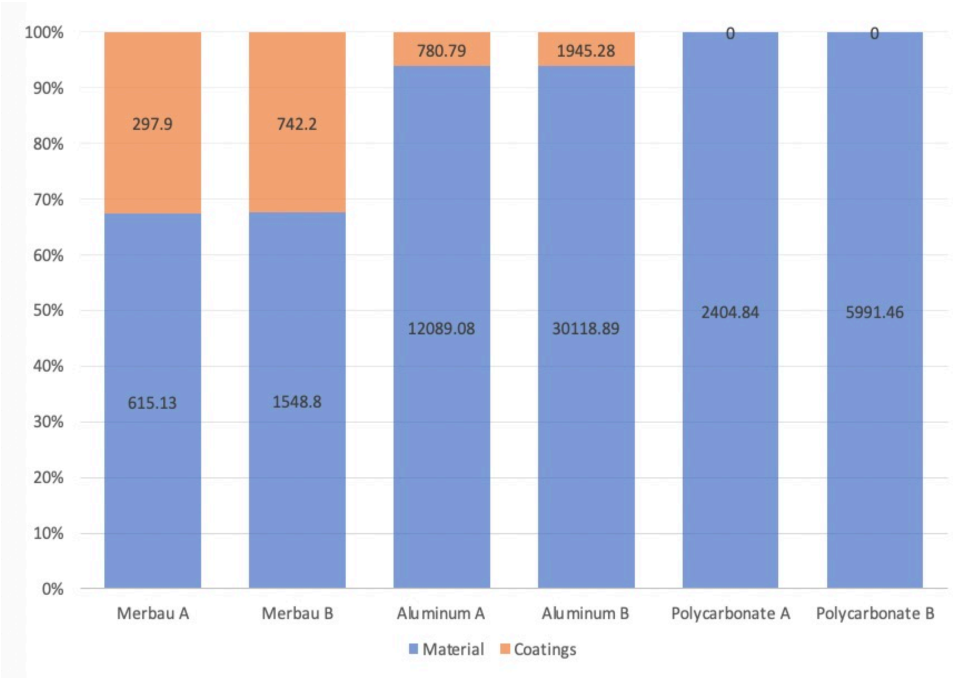


Figure 6.3 Breakdown of construction cost with respect to six proposed fixed external shading devices

Figure 6.3 shows the major construction cost elements. The main contributor is material, contributing 67%, 94% and 100% to the total construction cost. This takes into account all materials such as Merbau, Aluminium, and Polycarbonate. Meanwhile, protective coating contributes 33% and 6% to the total cost of construction regarding the Merbau and Aluminum.

6.3.2. Installation cost

It has been reported from the material suppliers that the installation cost of the fixed external shading devices consisting of transporting shading components from warehouse to the project site and assembling of the components into external shading devices on-site. Due to the difficulty of counting the number of spare parts required for assembly devices, the unit price of installation provided by the suppliers includes services of transportation and on-site assembly. This made it difficult to further break them down. Hence, the installation cost here mainly refers to the transportation. Investigation with the suppliers indicates that the unit prices of transportation are £0.006 per kg, £0.08 per kg and £0.06 per kg regarding Merbau, Aluminum, and Polycarbonate components. Installation costs have been estimated by multiplying the sum of weights including shading devices and protective coatings by their respective transportation unit prices (see Table 6.9). Figure 6.4 illustrates the breakdown of installation cost, the top three external shading designs with highest installation costs are Aluminum B, Aluminum A and Polycarbonate B. The installation cost of materials contributes more than 92% to the total installation cost, whilst the cost of coatings accounts for a small proportion and even can be ignored.

Table 6.9 Installation cost of the six proposed fixed external shading devices

Installation costs elements	**Cost (£)**					
	Merbau A	Merbau B	Aluminum A	Aluminum B	Polycarbonate A	Polycarbonate B
Material	3.53	8.90	128.17	322.70	42.41	106.78
Coatings	0.29	0.72	3.84	9.58	-	-
Total installation cost	**3.82**	**9.62**	**132.01**	**332.28**	**42.41**	**106.78**

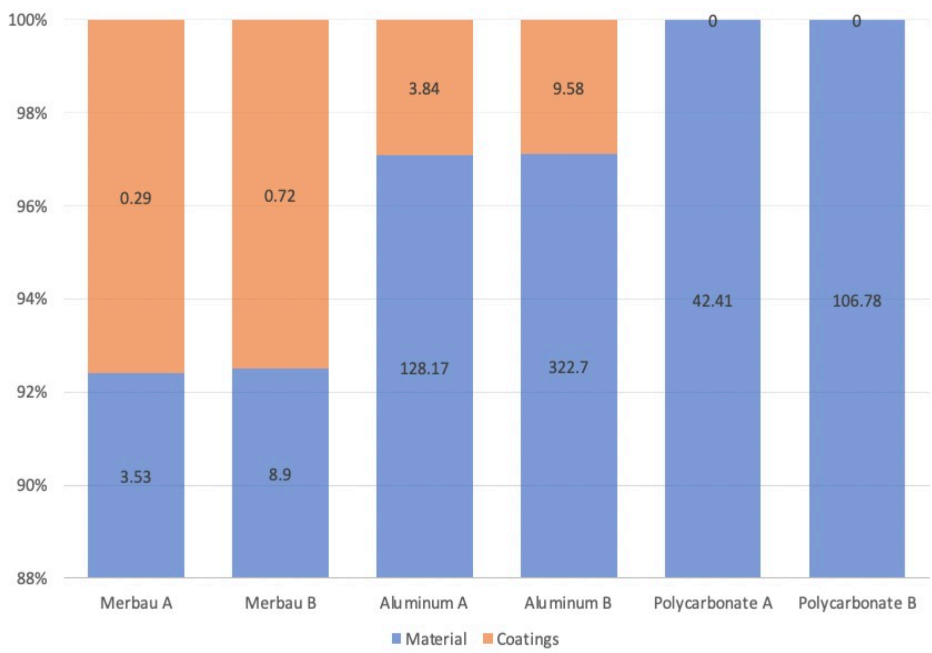


Figure 6.4 Breakdown of installation cost with respect to six proposed fixed external shading devices

6.3.3. Operation and maintenance cost (O&M)

The building operation costs related to external shading design mainly refers to utility costs, consisting of power consumption for lighting, cooling, and heating. As stated previously, the potential savings of annual electricity expenditure owing to the installation of a certain external shading devices can be estimated through simulation by CEEB 2024 and calculation by equations (5.2) and (6.3), as well as £0.088 kWh power unit price. This saving value can be regarded as a cash inflow or future energy-saving benefit that occurs every year.

During the maintenance stage, material suppliers point out that the fixed external shading devices required one-off replacement at the end of their life cycle. As listed in Table 6.5, the lifespan of Merbau is 40 years, Aluminum is 15 years and Polycarbonate is 7.5 years. As mentioned above, the lifespan of the entire building has been assumed to be 50 years, which means the replacement frequency of Merbau is 1, Aluminum is 3 and Polycarbonate is 6 during the maintenance stage. Moreover, protective paints are required to be coated covering the components for material protection. For example, water-based coatings need to be coated on the Merbau components every year, and fluorocarbon coatings need to be applied once after the Aluminum components have been made. During the maintenance stage, the frequency of use for water-based coatings and fluorocarbon coatings is 49 times and 3 times respectively. Hence, regular components replacement and protective paints coating are the major sources of maintenance costs, which can be considered as a cash outflow or cost that happens regularly in the future. The PV of O&M costs has been estimated at the discount rate of 5.04% for the 50 years studied period, using equation (6.1).

(1) Annual power consumption and electricity expenditure analysis

As stated in the last chapter, energy consumption simulation by BESI 2024 has been conducted for the reference building and designed building, to determine the values of energy-saving rate of building envelope regarding a certain external shading case. Similar to the building energy efficiency simulation in Chapter 5, based on the same simulation platform of GBSWARE, the annual power consumption for the reference building ($E_{sum,ref}$) and designed building ($E_{sum,des}$) can be obtained through simulation by CEEB 2024. The difference between the above two values can be regarded as the savings of power consumption (ΔE). Subsequently, the electricity expenditure saving regarding the six proposed external shading cases can be estimated through multiplying the value of (ΔE) by £0.088 kWh power unit price.

As listed in Table 6.10, simulation results indicate that the items of comprehensive power consumption for this studied educational building project consisting of cooling system, fresh air system and lighting system. Being a part of HVAC systems, the cooling system is an equipment combination composing of multiple components. Being controlled to regulate the air inside a building, cooling system can process the air sent into the building to a certain state and eliminate the indoor residual heat and humidity. Hence, the temperature and humidity can be maintained within the acceptable range of the human body. As an independent air treatment system installed in the ceiling of the kitchen or bathroom, the fresh air system composes of an air supply system and an exhaust system. Special equipment is used to send fresh air to one side of the closed room, and then discharges it to the outside through special equipment on the other side, forming a "fresh air flow field" to meet the indoor fresh air ventilation needs.

It can be concluded from the following results that the variation of annual comprehensive power consumption savings (ΔE) is related to the protruding length of the shading devices, but irrelevant to the materials that used to make into the shading components. As for the designed building, the longer the protruding length of the fixed external shading devices, the lower the comprehensive power consumption ($E_{sum,des}$) is, and the more savings of annual comprehensive power consumption can be. Take the example of the Merbau made shading devices, the values of (E_{sum}) of design building regarding Merbau A and Merbau B are 128,624 kWh/y and 128,097 kWh/y respectively. The protruding length of the shading device for Merbau B is longer than that of Merbau A. However, compared with Merbau A, the comprehensive power consumption ($E_{sum,des}$) of Merbau B simply reduces by 0.41% (This result is also capable to other two shading materials). Since the changes of comprehensive power consumption ($E_{sum,des}$) between Merbau A and Merbau B (which can also be regarded as Integrated shading A and Integrated shading I stated in the last chapter, without considering the shading materials) are not obvious, it can be further speculated that one of the reasons for lacking provisions to rate the fixed external shading devices in ASGB-2019 of China is that the impact of fixed external shading devices on comprehensive power consumption is not significant enough, receiving little attentions from the Chinese green building evaluation experts. Furthermore, the value of annual power consumption saving (ΔE), due to the installation of a certain fixed external shading device, might be overlooked by the Chinese experts, let alone the corresponding savings of electricity expenditure. The values mentioned above has not yet been reflected in the Chinese green building evaluation reports and the corresponding calculation documents which used for supporting evaluation.

Table 6.10 Annual power consumption and corresponding electricity expenditure saving regarding six fixed external shading devices

Building category	Shading alternative	Sub-item power consumption			Annual comprehensive power consumption (E_{sum}) (kWh/y)	Savings of power consumption (ΔE) (kWh/y)	Electricity unit price (£/kWh)	Savings of electricity expenditure (£/y)
		Cooling system E_c (kWh/y)	Fresh air system E_f (kWh/y)	Lighting system E_l (kWh/y)				
Reference building	-	115,235	32,056	18,536	165,827	-	-	-
Designed building	Merbau A (500,200)	78,287	32,027	18,310	128,624	37,203	0.088	3,273.86
	Merbau B (1000,600)	77,760	32,027	18,310	128,097	37,730	0.088	3,320.24
	Aluminum A (500,200)	78,287	32,027	18,310	128,624	37,203	0.088	3,273.86
	Aluminum B (1000,600)	77,760	32,027	18,310	128,097	37,730	0.088	3,320.24
	Polycarbonate A (500,200)	78,287	32,027	18,310	128,624	37,203	0.088	3,273.86
	Polycarbonate B (1000,600)	77,760	32,027	18,310	128,097	37,730	0.088	3,320.24

*Note: Power consumption data of cooling system, fresh air system and lighting system were collected through carbon emission simulation by CEEB 2024.

To obtain the values of annual power consumption saving (ΔE), simulation and calculation are required in Chinese scenario. Taking the Merbau made fixed external shading devices as an example, under the working condition of Merbau A, the comprehensive power consumption of the reference building ($E_{sum,ref}$) is 165,827 kWh/y, the comprehensive power consumption of the designed building ($E_{sum,des}$) is 128,624 kWh/y, which can be calculated by using the equation (5.2). The difference between the above two values, which is 37,203 kWh/y, calculating by using the equation (6.3), can be regarded as the annual power consumption savings (ΔE) by applying Merbau A shading strategy. Similarly, the annual power consumption savings (ΔE) by adopting Merbau B shading strategy is 37,730 kWh/y. That is to say, the annual power consumption savings (ΔE) of Merbau B is 1.4% higher than that of Merbau A. This result is also capable to other two shading materials, that is, the annual power consumption savings (ΔE) of Integrated shading I is 1.4% more than that of Integrated shading A. Furthermore, the annual saving of electricity expenditure regarding each external shading strategy has been estimated, listed in Table 6.10. These values have been obtained through multiplying the annual power consumption savings (ΔE) by local electricity unit price (0.088 £/kWh).

A further breakdown of comprehensive power consumption (E_{sum}) is illustrated in Figure 6.5, with respect to the six-shading circumstance. As stated previously, comprehensive power consumption consists of cooling system, fresh air system and lighting system, under this studied educational building circumstance. As it can been seen the values of power consumption regarding the above three systems for designed building in Table 6.10, changes simply occur in the values of cooling power consumption due to the dimension changes of protrusion regarding shading devices. The longer the protruding length of the fixed external shading device, the lower the cooling power consumption is, even though the minor changes of values. However, the power consumption of fresh air system and lighting system are not affected by the adoption of different fixed external shading devices. What's more, materials being used for making fixed external shading components have little impact on the power consumption of the aforementioned three system, e.g., cooling system, fresh air system and lighting system.

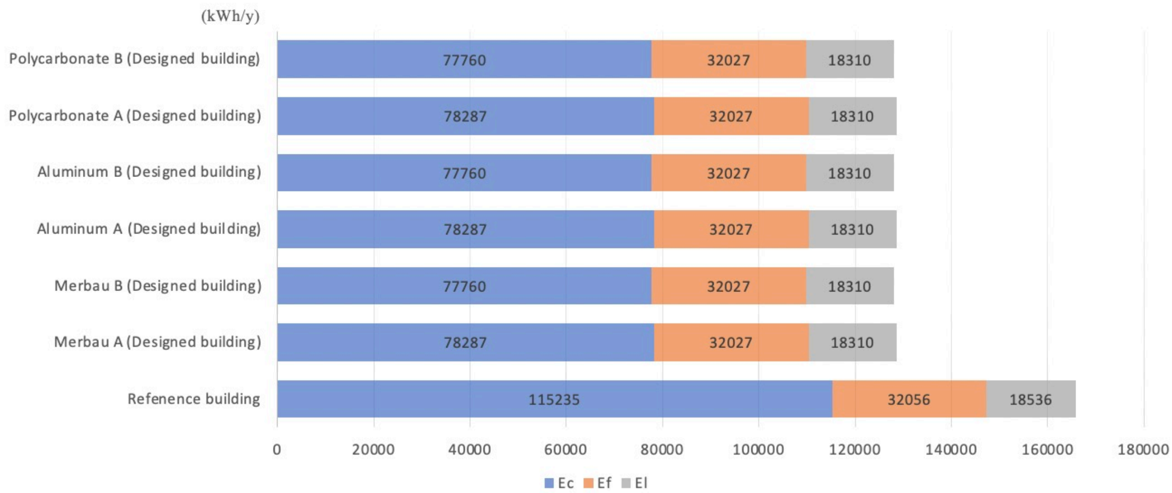


Figure 6.5 Breakdown of annual comprehensive power consumption regarding six proposed fixed external shading devices

(2) Cash flow and present value analysis

The cash flow statements of O&M costs have been generated regarding the six fixed external shading devices for 50 years life cycle period (see Appendix C to H). The cost elements of O&M stage consist of savings of electricity expenditure, materials, and protective coatings. The savings of electricity expenditure can be regarded as a cash inflow or future benefit each year, belonging to the utility element of operation cost. The elements of materials and protective coatings can be considered as a cash outflow or future maintenance cost, including the transportation costs from warehouse to the project site. The difference between the values of cash inflow and cash outflow is the net cash flow. The PV of O&M costs regarding the six proposed fixed external shading devices have been estimated by equation (6.1) at the discount rate of 5.04% for the life cycle period of 50 years.

Table 6.11 listed the PV of O&M costs. Taking the shading case of Merbau A as an example, the annual saving of electricity expenditure is estimated to be £3,273.86 (see Table 6.10), with a life cycle of 50 years, the present value is -£59,399.85. The shading materials will be removed and replaced in the 40th year, and the material cost to be paid (including transportation cost) is £618.66 (obtained by adding 615.13 listed in Table 6.8 and 3.53 in Table 6.9), with a present value of £86.55. Materials need to be coated with protective paint every year, and the cost of protective paint to be paid (including transportation cost) is £298.19 (obtained by adding 297.9 listed in Table 6.8 and 0.29 in Table 6.9), with a present value of £5,384.75 (see Appendix C). Hence, through summing up the above values, the present value of the total O&M cost of Merbau A is -£53,928.55. It is to be noted that the PV of the total O&M costs are all negative, representing the investment capitals regarding the installation of six fixed external shading devices at the initial stage of life cycle. Figure 6.6 illustrates the further breakdown of PV regarding O&M costs consisting of utility, material, and coatings. The PV of materials and coatings are located above the horizontal axis and equivalent to a deposit or income. Whilst the PV of utility is located below the horizontal axis and regarded as an investment. As for maintenance costs, the PV of coatings accounts for more than 98% of Merbau made external shading devices, while PV of materials accounts for 94% and 100% of aluminum and polycarbonate ones respectively. The investment value at the beginning of operation stage increases with the protruding length of the external shading devices, but irrelevant to the type of materials used for making devices. Calculation results shows that the top three initial investment regarding fixed external shading designs for O&M stage are Polycarbonate A, Merbau A and Aluminum A.

Table 6.11Present value of Operation and Maintenance costs regarding the six proposed fixed external shading devices

O&M costs elements	Cost (£) Discount rate:5.04%					
	Merbau A	Merbau B	Aluminum A	Aluminum B	Polycarbonate A	Polycarbonate B
Operation cost	**(59,399.85)**	**(60,241.36)**	**(59,399.85)**	**(60,241.36)**	**(59,399.85)**	**(60,241.36)**
Utilities	(59,399.85)	(60,241.36)	(59,399.85)	(60,241.36)	(59,399.85)	(60,241.36)
Maintenance cost	**5,471.30**	**13,633.66**	**10,615.13**	**26,449.46**	**4,598.33**	**11,458.45**
Material	86.55	217.92	9,974.54	24,853.45	4598.33	11,458.45
Coatings	5,384.75	13,415.74	640.60	1,596.01	-	-
Total O&M cost	**(53,928.55)**	**(46,607.70)**	**(48,784.71)**	**(33,791.90)**	**(54,801.52)**	**(48,782.91)**

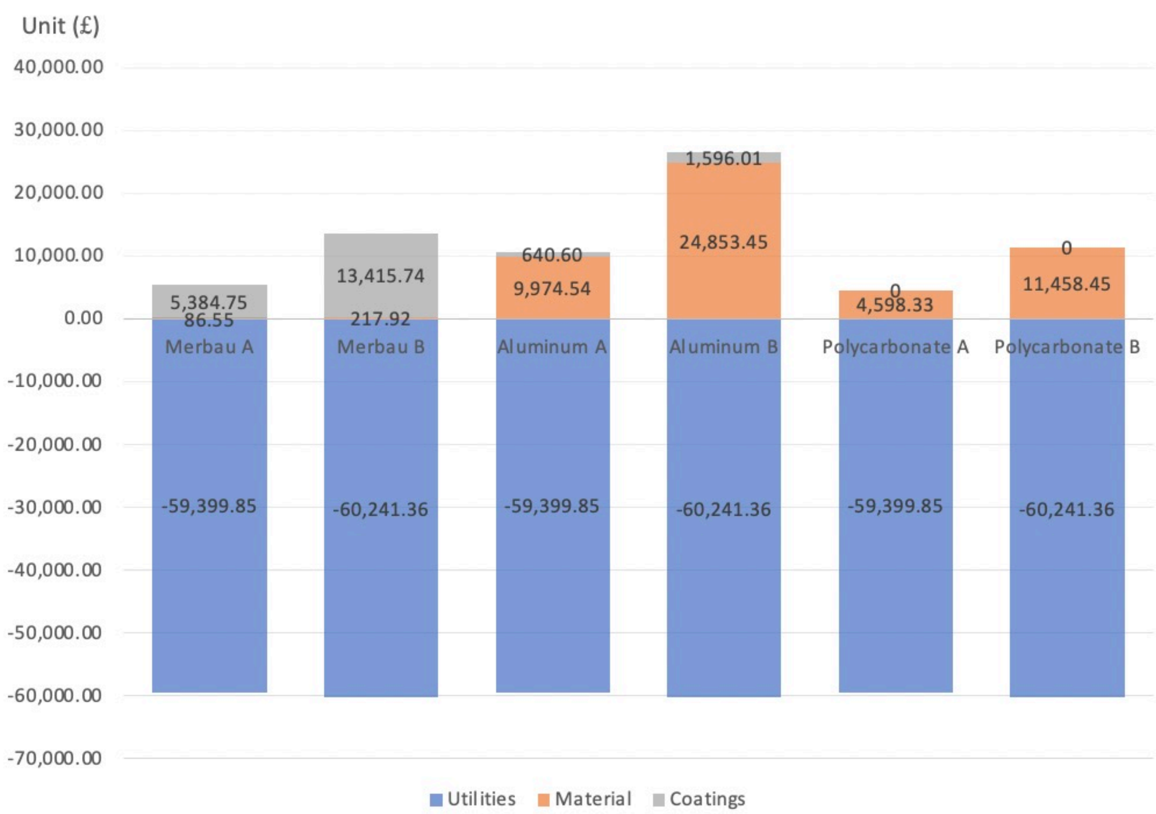


Figure 6.6 Breakdown of O&M costs regarding six proposed fixed external shading devices

6.3.4. Deposal cost

According to the feedback from the investigated renewable resource recycling companies, the above three selected shading materials can be recycled, e.g., Merbau, Aluminum, and Polycarbonate. The dismantling and dispose of recyclable materials cause less pollution to the environment, where environmentally friendly materials can be remade and reused again in the next production process. Hence, it can be assumed that the recyclable materials have more residual value than the traditional ones at the end of their life cycle. Table 6.12 listed the recycling information regarding the six external shading cases, including their recycling unit price, total weight, and total price at each time of recycling. The lifespan of each material has been obtained through the previous investigation with the material suppliers (see Table 6.5). It can be inferred from the life cycle of materials and the 50-year lifespan of the studied educational building that the demolition and recycling year of Merbau is the 40th and 50th year. Aluminum is the 15th, 30th, 45th and 50th year. Polycarbonate is the 8th, 16th, 24th, 32nd, 40th, 48th and 50th years. The PV of the residual with respect to the studied fixed external shading devices have been estimated by formula (6.1) (see Table 6.13). Similar with the PV results of O&M costs stated in the last section, the PV of the disposal costs (residual value of materials) are negative, which can be regarded as investment at the life cycle initial stage, illustrating the realizable value of recyclable materials. Calculation results reveals that the top three initial investment regarding external shading designs for disposal stage are Aluminum B, Polycarbonate B, and Aluminum A.

Table 6.12 Recycling information of the six proposed fixed external shading devices

External shading case	Recycling price per unit (£/kg)	Total weight (kg) for a single replacement	Total recycling price (£) for a single replacement	Year of recycling
Merbau A	0.01	637.049	6.37	T40, T50
Merbau B	0.01	1,602.709	16.03	T40, T50
Aluminum A	1.894	1,650.129	3,125.34	T15, T30, T45, T50
Aluminum B	1.894	4,153.469	7,866.67	T15, T30, T45, T50
Polycarbonate A	1.623	706.8	1,147.14	T8, T16, T24, T32, T40, T48, T50
Polycarbonate B	1.623	1,779.6	2,888.29	T8, T16, T24, T32, T40, T48, T50

Table 6.13 Disposal cost of the six proposed fixed external shading devices

Disposal costs elements	**Cost (£) Discount rate:5.04%**					
	Merbau A	Merbau B	Aluminum A	Aluminum B	Polycarbonate A	Polycarbonate B
Residual value of materials	(1.44)	(3.61)	(2,819.02)	(7,095.65)	(2,253.60)	(5,674.15)
Total disposal cost	**(1.44)**	**(3.61)**	**(2, 819. 02)**	**(7,095.65)**	**(2,253.60)**	**(5,674.15)**

6.3.5. LCCA of the six proposed fixed external shading devices

Table 6.14 illustrates the NPV which has been derived by summing up the PV of construction, installation, operation, maintenance, and disposal costs for each fixed external shading devices by using equation (6.2). As listed in Table 6.14, the values of NPV (LCC) regarding the six proposed fixed external shading devices are negative, representing the requirement of investment at the initial life cycle stage. The initial investment regarding the external shading designs from high to low are Polycarbonate A, Merbau A, Polycarbonate B, Merbau B, Aluminum A and Aluminum B, with the corresponding NPV of £54,607.87, £53,013.14, £48,358.82, £44,310.69, £38,601.86, £8,491.10 respectively.

Table 6.14 LCC comparison among the six proposed fixed external shading devices

Cost elements	**Cost (£) Discount rate:5.04%**					
	Merbau A	Merbau B	Aluminum A	Aluminum B	Polycarbonate A	Polycarbonate B
Construction	**913.03**	**2,291.00**	**12,869.87**	**32,064.17**	**2,404.84**	**5,991.46**
Material	615.13	1,548.80	12,089.08	30,118.89	2,404.84	5,991.46
Coatings	297.90	742.20	780.79	1,945.28	-	-
Installation	**3.82**	**9.62**	**132.01**	**332.28**	**42.41**	**106.78**
Material	3.53	8.90	128.17	322.70	42.41	106.78
Coatings	0.29	0.72	3.84	9.58	-	-
Operation	**(59,399.85)**	**(60,241.36)**	**(59,399.85)**	**(60,241.36)**	**(59,399.85)**	**(60,241.36)**
Utilities	(59,399.85)	(60,241.36)	(59,399.85)	(60,241.36)	(59,399.85)	(60,241.36)
Maintenance	**5,471.30**	**13,633.66**	**10,615.13**	**26,449.46**	**4,598.33**	**11,458.45**
Material	86.55	217.92	9,974.54	24,853.45	4,598.33	11,458.45
Coatings	5,384.75	13,415.74	640.60	1,596.01	-	-
Disposal	**(1.44)**	**(3.61)**	**(2,819.02)**	**(7,095.65)**	**(2,253.60)**	**(5,674.15)**
NPV(LCC)	**(53,013.14)**	**(44,310.69)**	**(38,601.86)**	**(8,491.10)**	**(54,607.87)**	**(48,358.82)**

6.4. Discussion and inferences

The illustration and associated descriptions regarding the green educational building case which presented in the previous chapters give the key steps to assess the energy-saving impact of various fixed external shading devices on the studied building. The assessment method has been developed to meet the requirements of being generic, formal, flexible, and time-efficient for implementation in the Chinese context. In this chapter, with the intentions of assessing the economic impact of the external shading devices, LCCA has been carried out in this part of research, with respect to six proposed fixed external shading devices for a green educational building in Shenzhen, with the climate characteristics of hot summer and warm winter. To determine the fixed external shading strategies to be studied, an in-dept investigation has been conducted with the local external shading products manufactures and construction material suppliers, to collect the relevant product information, costs, and processes from production to disposal, etc. Six fixed external shading strategies, namely Merbau A, Merbau B, Aluminum A, Aluminum B, Polycarbonate A and Polycarbonate B have been determined for LCCA. Since the construction and installation costs occur at the beginning of life cycle, the PV formula has been used to calculate the corresponding PV of costs during O&M and disposal stages, so as to estimate the corresponding NPV of LCC. Comparisons have been performed amongst the six cases during each stage of 50-years life cycle. To support the estimation of the PV regarding O&M costs, building power consumption simulation has been carried out by a Chinese local building carbon emission software named CEEB 2024, to collect the annual comprehensive power consumption of the studied educational building. This is to estimate the annual potential savings of power consumption and corresponding electricity expenditure. Further investigation has been conducted with the local renewable resource recycling companies, to collect the information of disposal process and recycling prices regarding the three recyclable materials (e.g., Merbau, Aluminum, and Polycarbonate).

The construction costs are due to material purchase and paint coatings for the fixed external shading devices. Operation costs mainly refer to the utility expense. Maintenance costs mainly include the regular replacement of fixed external shading devices and the regular spraying of protective coatings. Disposal costs occur during the removal of the shading components and their transportation back to the recycling center. Analysis results can be inferred that:

(1) Aluminum B is the case with the highest construction cost, £32,064.17, including material purchase and coatings.
(2) Aluminum B is the case with the highest installation cost, £332.28, including transportation and on-site assembly.
(3) Calculated by the PV formula and discount rate of 5.04% for 50-years life cycle period, the total O&M costs regarding six external shading cases are negative, which are equivalent to investment capitals regarding the shading devices installation at the beginning of life cycle. Polycarbonate A is the case with the highest investment capital for O&M stage, £54,801.52.
(4) All the PV of disposal costs under the six shading design conditions are negative, regarding as investment capitals. Aluminum B is the case with the highest investment capital, £7,095.65.

With respect to the NPV of LCC, Polycarbonate A has the highest initial investment, £54,607.87, followed by Merbau A, Polycarbonate B, Merbau B, Aluminum A and Aluminum B, with the NPV value of £53,013.14, £48,358.82, £44,310.69, £38,601.86, £8,491.10 respectively. Results of LCCA reveals that the implementation of Polycarbonate A to make fixed external shading devices has the highest initial investment at the beginning of its life cycle.

6.5. Summary

This chapter presents a process of LCCA to demonstrate the use of the proposed economic assessment method to infer a certain fixed external shading device with the initial investment from high to low at the beginning of its life cycle for the studied educational building. Various research methods such as LCCA, building power consumption simulation (CEEB 2024) and comparative study have been applied in this part of research, for cost data collection and PV estimation of corresponding costs during construction, installation, O&M, and disposal stages. It examines six shading design options of a three-storey educational building in order to illustrate the usefulness of economic assessment method. Analysis results reveals that Polycarbonate A is the case with the highest initial investment amongst the six shading alternatives, which NPV of LCC is £54,607.87. This is followed by Merbau A, Polycarbonate B, Merbau B, Aluminum A and Aluminum B, with the corresponding NPV value of £53,013.14, £48,358.82, £44,310.69, £38,601.86, £8,491.10 respectively. This economic aspect of the research aims to apply the assessment method on a specific building case as an evidence of its effectiveness, which is further substantiated through a multi-criteria assessment process presented in Chapter 8.

Chapter 7. Life Cycle Carbon Emission Assessment

In this chapter, the use of the proposed environmental assessment method is demonstrated in the studied green educational building in Shenzhen. The intention is to assess the $LCCO_2$ emission impact regarding six fixed external shading devices on building for subsequent comprehensive evaluation. Multiple methods such as carbon emission simulation by CEEB 2024, a case study and a comparative study have been adopted throughout 50-year building lifespan. An overview of $LCCO_2A$, the application of $LCCO_2A$ and detailed analytical results are discussed in this chapter.

7.1. Overview of life cycle carbon emission assessment

The concept of 'carbon emissions' usually refers to all GHG emissions. GHGs are usually converted into carbon dioxide equivalents, called 'CO_{2e}', based on the global warming potential of a 100-year base period. The key to low-carbon design of building structures lies in the scientifically assessment regarding the building carbon emissions throughout their life cycle (Xu *et al*., 2023). The $LCCO_2A$ considers all the carbon equivalent emissions generated by a building at different life cycle stages (Chau *et al*., 2015). Similar studies on building carbon emissions are common in developed districts and countries. The carbon emissions produced by buildings in different regions throughout their life cycle present obvious regional characteristics, resulting from various regional climate types, technological levels, and management policies. In a study related to building $LCCO_2$ emissions, Peng (2016) pointed out that the carbon emissions in developed countries were higher than those in developing regions at the stage of building materials production. Moreover, during the phrase of raw materials procurement and building materials production, the carbon emissions in developed countries were lower than those in developing regions. Hence, the carbon emissions simulation throughout the life cycle of buildings is more complex that their calculation results within various countries reveal huge differences. This is the reason why carbon emission calculation methods adopted in the developed countries cannot be equally applicable to developing regions. Furthermore, the research method adopted in the study of building's $LCCO_2$ emissions which carried out by scholar Peng (2016), was a combination of BIM and Ecotec, focused on a developing Chinese city of Nanjing. However, there is no updated software version of Ecotect since 2011.

To carry out building carbon emission analysis in the context of China, a commonly used simulation software in Chinese construction industry would be more suitable than other software, as it has been put into practical use by various local architectural design institutes and green building evaluation agencies, e.g., CEEB 2024 on the building simulation platform of GBSWARE. Even though its practicability in the actual work, there is hardly research has been done by using this practical software, especially focus on a certain construction component, e.g., the fixed external shading devices. Hence, subsequent analysis will focus on the application of this specific software to conduct $LCCO_2$ emission analysis regarding the fixed external shading design based on the studied educational building, so as to assess the impact of various external shading design on building's carbon emission. The analysis results and inference for this part of research will form the basic contributions to this specific research area.

7.1.1. CEEB 2024

Developed by Beijing Gbsware Co., Ltd in 2023, CEEB is applicable to the calculation and analysis of carbon emissions throughout the life cycle of a building, covering different stages such as production and transportation of building materials, construction and demolition, operation, and maintenance. The calculation model can undertake simulation results such as energy consumption calculation and photovoltaic power generation on the GBSWARE platform. This software currently has two versions (CEEB 2023 and CEEB 2024), which can be used for carbon emission calculations for building energy conservation and green building evaluation. It is a supporting tool for the implementation of relevant standards for building carbon emissions. There are several advantages in CEEB 2024 (GBSWARE, 2025b):

(1) It is developed based on the national standard of GCEEREAB-2021 and SBCEC-2019.
(2) It is applicable to carbon emission estimation in the feasibility study and scheme stage of a building, and the carbon emission accounting in the construction drawing stage. There is no need to re-build model in the feasibility study stage. Relevant report can be calculated and outputted by simply input the project profile with one click.
(3) It supports the entire life cycle of a building, including production and transportation of building materials, construction and demolition, operation, and maintenance, etc.
(4) Carry out dynamic simulation of building operation energy consumption hourly, supporting quick and professional settings, and generating reliable carbon emission calculation results.

(5) Built-in comprehensive typical building material index library for the convenience of calling and quickly estimating building material carbon emissions.
(6) Share models and system equipment information among a series of software on GBSWARE platform.
(7) Provides multiple calculation methods to facilitate estimation and detailed calculation at each stage.
(8) Import the material list and automatically match the carbon emission factor of the building materials.
(9) Automatically output the 'Building Carbon Emission Analysis Report'.

7.1.2. Stages of life cycle carbon emission

For the time being, there is no unified standard for the division of building life cycle. Three major life cycle stages have been divided into material preparation, building operations and demolition in some previous studies (Gustavsson and Sathre, 2006; Ramesh *et al*., 2010; Tian *et al*., 2011), while some prefer the following stages of planning and design, construction, operation, and end-of-life, others have also included the aspects of on-site construction, material recycling (Gustavsson *et al*., 2010; Zhu and Ying, 2012; Li *et al*., 2013), etc. A holistic approach requires that all these stages being combined in the sustainability analysis. The early stages of planning and design are the best time to greatly influence the sustainability-related impacts of buildings. The LCCA in the last chapter divided the building life cycle into construction, installation, operation and maintenance, and disposal stage. As for building carbon emissions, the amounts of emissions are produced by a building during its construction, demolition, and operation stages. The source of carbon emissions mainly comes from fuel combustion release. Strictly speaking, the indirect carbon emissions account for a larger proportion of the building body (excluding production and life activity within the building), while the direct carbon emissions are relatively small. The carbon emission factor is a coefficient that corresponds energy and material consumption to carbon emissions. It is used to quantify the carbon emissions of related activities at different stages of a building. From the perspective of carbon emission sources, carbon emissions throughout the life cycle of a building mainly include several aspects:

(1) Fossil energy consumption and energy consumption during the production and transportation of building materials and equipment.
(2) Carbon emissions during the building construction phase.

(3) Carbon emissions during the operation phase.
(4) Carbon emissions during the building demolition phase.

According to requirements of 'Building Carbon Emission Calculation Guidelines (Trial)' (Hereinafter referred to as BCECG) issued by the Department of Housing and Urban-Rural Development in Guangdong Province (Hereinafter referred to as DOHURD-GD) in 2021, the $LCCO_2$ emissions of building have been divided into four main stages (see Figure 7.1), e.g.,

(1) Production and transportation of building materials
(2) Building construction
(3) Building operation
(4) Building demolition (DOHURD-GD, 2021)

This can be used to calculate the carbon emission amount of the completed buildings and can also be used to estimate the building carbon emissions during the building design stage in BESI 2024.

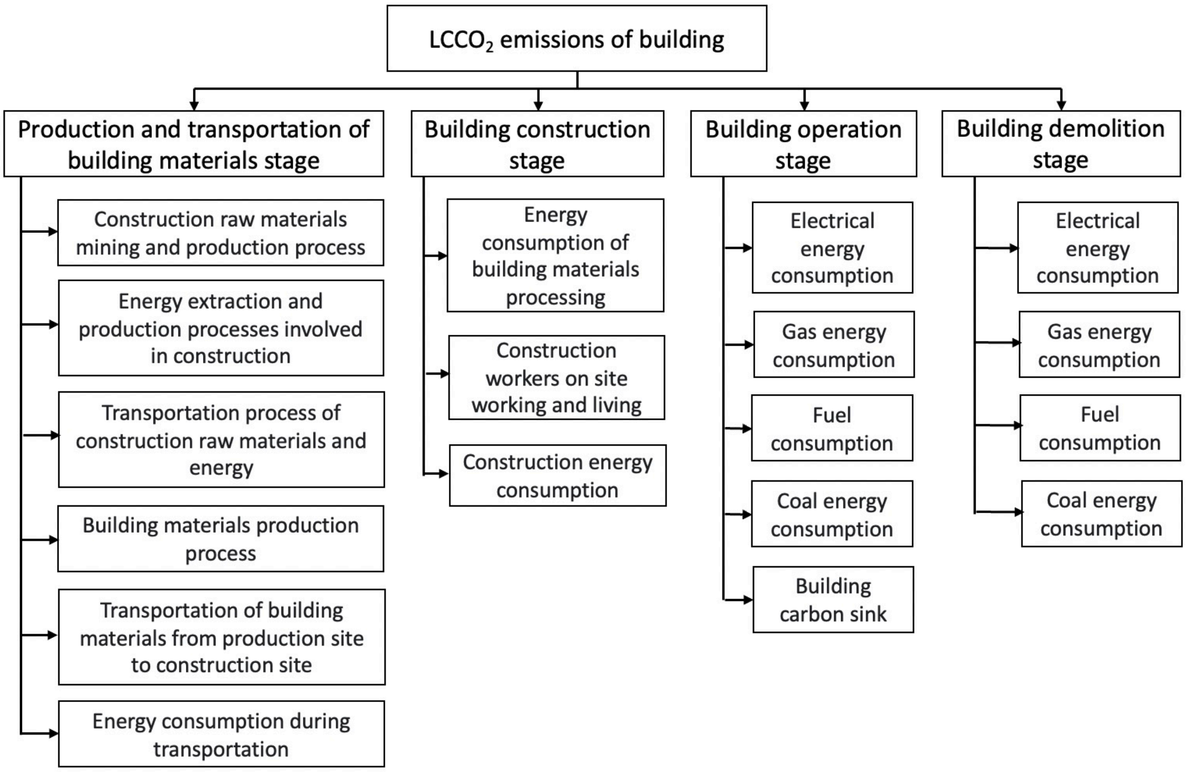


Figure 7.1 $LCCO_2$ emissions of buildings during different building stages

(Source: DOHURD-GD, 2021.)

7.2. Application of life cycle carbon emission assessment

The assessment process of building $LCCO_2$ emission calculation method is presented below. This includes the basic calculation equation of CO_2 emission amounts at different life cycle stages, the estimation of the total CO_2 emission amount throughout a building's whole life cycle, data collection regarding material usage during 50-year building lifespan and CO_2 emission factors, as well as data import process (MOHURD, 2019b; DOHURD-GD, 2021). CEEB 2024 has been applied for CO_2 emissions estimation and comparison regarding six proposed fixed external shading devices over the whole life cycle process for the studied educational building. The calculation equations listed below have been set up in the CEEB system.

7.2.1. Calculation formulas at different building life cycle stages

(1) Building materials production and transportation stage

'Standard for Building Emission Calculation' GB/T 51366-2019 (Hereinafter referred to as SBCEC-2019) stated that CO_2 emissions of building materials have been divided into production and transportation stages. The CO_2 emissions amount of building material production and transportation stages can be estimated by the equation (7.1) (MOHURD, 2019b):

$$C_{JC} = \frac{C_{SC}+C_{YS}}{A} \tag{7.1}$$

where C_{JC} is the CO_2 emissions amount per unit building area during the production and transportation stages of building materials (kg CO_2e/m^2). C_{SC} is the CO_2 emissions amount during the production stage of building materials (kg CO_2e). C_{YS} is the CO_2 emissions amount during transportation stage of building materials (kg CO_2e). A is the construction area (m^2). All the above CO_2 emission value can be generated through simulation calculation by CEEB 2024 at this specific stage.

(2) Building construction stage

Carbon emissions of building construction stage refers to the comprehensive carbon emissions during the building construction process. Building construction projects are generally divided into six major divisions, e.g., 1) basic engineering, 2) decoration engineering, 3) structural engineering, 4) installation engineering, 5) site transportation, and 6) construction temporary installation. Carbon emissions during the building construction stage mainly come from three aspects:

1) The energy consumption of building materials processing, including the processing of concrete, and the carbon emissions generated by the production and processing of prefabricated components for prefabricated buildings.
2) The carbon emissions generated by construction personnel working and living on site, including air conditioning and lighting in work sheds.
3) The construction energy consumption, including electricity consumption and fuel consumption of construction equipment.

The calculation methods for building carbon emissions are divided into two categories (DOHURD-GD, 2021):

1) Carbon emission calculation based on actual construction energy consumption data.
2) Carbon emission calculation based on estimated construction energy consumption, including construction energy consumption quota method, project budget and final accounting calligraphy, and empirical formula method.

In this part of research, CEEB 2024 has been applied for building carbon emission simulation and estimation based on the empirical formula method in the construction stage. This method estimates the carbon emission with the coarsest granularity. It is only applicable to engineering projects that do not have any data related to energy consumption, but still require carbon emission accounting during this stage. This method can be used to estimate the carbon emissions per unit area of the building through empirical formulas, thus, to calculate the estimated total carbon emissions of the entire construction process considering building area. The CO_2 emission of building construction stage can be estimated by equations (7.2) and (7.3) (DOHURD-GD, 2021):

$$Y = X + 1.99 \tag{7.2}$$

$$C_{JZ} = Y * A \tag{7.3}$$

where X is the number of building layers. Y is the CO_2 emission amount per unit area of building construction stage (kg CO_2/m^2). C_{JZ} is the CO_2 emission amount of building construction stage (kg CO_2). A is total construction area (m^2), which is 2,138.25 m^2 in this research (mentioned in section 3.1.2).

(3) Building operation stage

The carbon emission calculation during the operation phase takes a complete year as the timed unit. For the carbon emission calculation during the entire life cycle of the building, it is only necessary to sum up the carbon emissions for each year during the operation phase. The lifespan of the studied educational building is assumed to be 50 years. The carbon emission during the operation phase represented by 'C_M' is the sum of the carbon emissions converted from all types of energy consumed during the building's operation phase. This includes the carbon emissions converted from energy consumption generated by various energy-using systems such as air conditioning systems, lighting systems, and power equipment systems. Table 6.7 listed the parameters of cooling and lighting systems which have been set in CEEB 2024 system. Carbon emissions converted from various energy consumptions during the operation phase includes electricity, gas, oil, coal, etc. All types of energy consumption should be the total energy consumption provided by the building minus the energy consumption provided by renewable energy. Assuming that a total of n types of energy is consumed during the operation phase, the carbon emission amount can be estimated by equation (7.4) (DOHURD-GD, 2021):

$$C_M = \sum_{i=1}^{n}(E_i * Q_i) \tag{7.4}$$

where C_M is the carbon emission of building operation stage. E_i is the usage of type i energy source. Q_i is the carbon emission factor of type i energy source. To calculate the total CO_2 emission amount at this specific stage, the value of C_M should be subtracted from the value of Cp, which will be further discussed in section 7.3.4.

There are three methods for calculating energy consumption at this stage, e.g., 1) energy consumption monitoring method, 2) energy consumption statistics method, and 3) energy consumption simulation method. In this part of research, CEEB 2024 has been adopted as the energy consumption simulation software for carbon emission at this building operation stage.

(4) Building demolition stage

Similar to building operation stage, energy consumption in building demolition stage mainly includes electricity, gas, oil, coal, etc. Electricity consumption in this stage mainly refers to the power consumption generated by the office activities of demolished building and demolition sites. From the perspective of specific consumption types, electricity consumption for heating and cooling in office spaces, electrical lighting in office and demolition spaces, and energy consumption of various types of demolition equipment are included. In this part of research, CEEB 2024 has been adopted for carbon emission simulation at this specific stage. According to the empirical formula method which mentioned in ‘Building Carbon Emission Calculation Guideline (Trial)’, as well as the practical carbon emission calculation method of building demolition stage which demonstrated in the ‘Green Carbon Reduction Measures Report’, the CO_2 emission amount at this stage C_{CC} (kg CO_2) can also be roughly verified by equations (7.2) and (7.3) (DOHURD-GD, 2021).

(5) Carbon sink of buildings

Building carbon sink refers to the amount of carbon dioxide absorbed and stored by greening and vegetation from the air within the scope of a specified building project. This includes building greening, which achieves carbon sinks through the carbon fixation and oxygen release effects of photosynthesis of plants. The building carbon sink area can be obtained from the building's landscape map. The carbon sink can be estimated by equation (7.5) (DOHURD-GD, 2021):

$$Cp = \sum_{i=1}^{n}[|C_i| * Q_i] \tag{7.5}$$

where Cp is carbon sink of buildings. $|C_i|$ represents the amount of the type i carbon sink. The unit of it depends on the type of carbon sink, generally is m^2. Q_i represents the carbon sink factor of the type i carbon sink.

7.2.2. Estimation of life cycle carbon emission amount

The ‘Building Carbon Emissions Guideline (Trial)’ stipulates the carbon emission calculation methods for the stages of building construction, operation, and demolition. At the same time, it is proposed that in the calculation of carbon emissions throughout the building life cycle, the carbon emissions of the building materials production and transportation stages can be estimated in accordance with the provisions of SBCEC-2019. Thus, the CO_2 emission of building life cycle can be estimated by equation (7.6) (MOHURD, 2019b; DOHURD-GD, 2021):

$$LCCO_2 = C_{JC} * A + C_{JZ} + C_M + C_{CC} - C_p \tag{7.6}$$

7.2.3. Data collection

Data collection regarding material usage of six proposed fixed external shading devices in 50-year building lifespan, as well as carbon emission and carbon sink factors of various construction materials for this studied educational building is presented as follow:

(1) Material usage of fixed external shading devices during 50-year building lifespan

Table 7.1 listed the usage of shading materials and coatings regarding fixed external shading devices during 50-year building lifespan. The values of density, lifespan, volume, and weight of single usage of the materials and coatings are obtained from Table 6.5. The value of frequency represents the replacement of materials and coatings during 50-year life cycle by referring to the recycling year listed in Table 6.12. The volume and weight of the total usage are obtained by multiplying the ones of single usage by the replacement frequency respectively.

Table 7.1 Material usage of fixed external shading devices (50-year building lifespan)

Material		**Merbau**	**Water-based coating**	**Aluminum**	**Fluorocarbon coating**	**Polycarbonate**
Density (kg/m^3)		1,000	1,150	2,720	1,500	1,200
Lifespan (year)		40	-	15	-	7.5
Volume of single usage (m^3)	Integrated shading A (500mm, 200mm)	0.589	0.0418	0.589	0.032	0.589
	Integrated shading I (1000mm,600mm)	1.483	0.1041	1.483	0.0798	1.483
Weight of single usage (kg)	Integrated shading A (500mm, 200mm)	589.00	48.049	1,602.08	48.049	706.80
	Integrated shading I (1000mm,600mm)	1,483.00	119.709	4,033.76	119.709	1,779.60
Frequency		2	50	4	4	7
Volume of total usage (m^3)	Integrated shading A (500mm, 200mm)	1.178	2.09	2.356	0.128	4.123
	Integrated shading I (1000mm,600mm)	2.966	5.205	5.932	0.3192	10.381
Weight of total usage (kg)	Integrated shading A (500mm, 200mm)	1,178.00	2,402.45	6,411.20	192.196	4,947.60
	Integrated shading I (1000mm,600mm)	2,966.00	5,985.45	16,135.04	478.836	12,457.20

(2) Carbon emission factors

Table 7.2 - Table 7.4 listed the carbon emission and carbon sink factors required for calculating carbon emission amounts during different building stages, as well as the building's $LCCO_2$ emission amount. As for the carbon emission factors of building materials production and transportation stage listed in Table 7.2, most of the carbon emission factors are the default parameters in the database of CEEB. The carbon emission factors regarding the materials and

coatings that used to make into external shading devices, e.g., raw aluminum, fluorocarbon coating, polycarbonate, merbau, water-based coating, they are collected through information query with the website of Baidu (Baidu, 2024) and China products carbon footprint factors database (CPCD, 2024). As for the carbon sink stage, carbon sink factors are collected through reviewing BCECG (DOHURD-GD, 2021). The carbon emission factors with respect to the cooling system, air conditioning fan and lighting system during the building operation stage, are collected by referring to the average carbon emission factor of southern China regional power grid which stated in the SBCEC-2019 (MOHURD, 2019b). Since the database is built based on the Chinese building parameters, most of the referred sources of carbon emission factors are from China. 3D model of the kindergarten building which has been used in the previous chapters for energy-saving and economic assessments has been imported into the CEEB software for the subsequent building carbon emission simulation calculation. The usage of the building body and the corresponding carbon emission factors are kept unchanged, only considering the impact of the material usages and carbon emission factors regarding various fixed external shading designs on the carbon emissions of the building throughout 50-year lifespan. Further carbon emission analysis with respect to six proposed fixed external shading devices is discussed in detail in section 7.3.

Table 7.2 Carbon emission factors of commonly used construction materials for the studied educational building during building materials production and transportation stages

Construction material	**CO_2 emission factor**			
	Building materials production stage ($kgCO_2e$/unit)	Unit	Building materials transportation stage ($kgCO_2e/t \cdot km$)	Unit
Concrete	340.00	m^3	0.115	km
Rebar	2,340.00	t	0.115	km
Section steel	2,365.00	t	0.115	km
Cement	735.00	t	0.115	km
Ready mixed mortar	370.00	t	0.115	km
Sand	3.00	m^3	0.115	km
Extruded polystyrene foam board	534.00	m^3	0.115	km
NEA insulation leveling gel	534.00	m^3	0.115	km
Building blocks	349.00	m^3	0.115	km
Brick	336.00	m^3	0.115	km
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	129.50	m^2	0.115	km
Insulation door (multifunctional door)	48.30	m^2	0.115	km
Ceramics	19.50	m^2	0.115	km
Coating	6,550.00	t	0.104	km

Cable	94.10	kg	0.334	km
Pipes	3.60	kg	0.115	km
Raw aluminum	18,790.00	t	0.115	km
Fluorocarbon coating	3,600.00	t	0.334	km
Polycarbonate	1,370.50	t	0.115	km
Merbau	178.00	m^3	0.334	km
Water-based coating	231.00	t	0.334	km

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database; Baidu, 2024; CPCD, 2024.)

Table 7.3 Carbon sink factors for the studied educational building at carbon sink stages

	Category	CO_2 sink factor
Carbon sink stage	Tall grass flower beds or tall grass fields (height about 1.0m, soil depth >0.3m)	1.15 kg/m^2·a
	Grass flower bed, natural wild grass, lawn, aquatic plants	0.5 kg/m^2·a

(Source: DOHURD-GD, 2021.)

Table 7.4 Carbon emission factors for the studied educational building during building operation stage

	Carbon emission factors
Cooling system	0.5271 kgCO_2/kWh
Air conditioning fan	0.5271 kgCO_2/kWh
Lighting system	0.5271 kgCO_2/kWh

(Source: MOHURD, 2019b.)

7.2.4. Data import process

The process of importing information into the carbon emission software system is discussed in this section. The criteria used for environmental sustainability assessment is $LCCO_2$ emission amount. The components of $LCCO_2$ emissions include four stages: 1) building material production and transportation, 2) building construction, 3) building operation, and 4) building demolition. The imported data regarding material usage and corresponding carbon emission factors at building material production and transportation stage are obtained based on Table 7.1 and Table 7.2. During the building construction and demolition stages, the function button of 'Empirical formula method' has been selected to perform carbon emission simulation. The construction area and the number of floors is involved in the estimation of carbon emission amounts in these two stages. In the building operation stage, '0.5271' has been typed in the input box as the carbon emission factor value listed in Table 7.4, to calculate the carbon emission amount of power consumption. At the building carbon sink stage, data of green area have been typed in the input box according to the general floor plan of the studied educational building. Detailed analysis of carbon emission of each life cycle stage will be discussed in the next section.

7.3. Analysis of the assessment results

According to the total volume and weight of the materials and coatings required for making fixed external shading devices during 50-years lifespan of building (see Table 7.1), the carbon emission amounts at building material production and transportation stage can be estimated through simulation by CEEB 2024. As for the rest building materials, the amounts of their corresponding carbon emission are automatically generated in CEEB system based on the same building parameters. After inputting the relevant data into the database of CEEB, the CO_2 emission amounts of different building stages for each shading case can be estimated. This analysis process is illustrated as follow:

7.3.1. Building materials production and transportation stage

Carbon emission amount with respect to six proposed fixed external shading devices during the building material production and transportation stages are discussed respectively.

(1) Building materials production stage

The CO_2 emission amounts of a variety of construction materials during building materials production stage with respect to six proposed fixed external shading devices have been obtained, under 50-year building lifespan circumstance (see Appendix I-N). The amounts of CO_2 emission of different construction materials have been estimated by multiplying the total usage of the materials (see Table 7.1) by CO_2 emission factors (see Table 7.2). These results are automatically generated by CEEB simulation. Through summing up the CO_2 emission amount of various building materials, the total CO_2 emission amounts of different external shading designs during the materials production stage (C_{SC}) can be estimated. The CO_2 emission amount of reference building at this stage is 1,480.29 tCO_2e. Figure 7.2 listed the total carbon emission amount of six proposed external shading designs at building materials production stage. The total carbon emission amounts regarding six external shading designs at this specific stage from high to low are Aluminum B of 1,785.29 tCO_2e, Aluminum A of 1,601.42 tCO_2e, Polycarbonate B of 1,497.36 tCO_2e, Polycarbonate A of 1,487.07 tCO_2e, Merbau B of 1,482.20 tCO_2e and Merbau A of 1,481.05 tCO_2e. Further discussion below is conducted from the perspective of shading materials and external shading design dimension:

1) Shading materials

Through comparison of the total CO_2 emission amounts, with respect to different shading materials, the ones regarding the base shading options between merbau and polycarbonate made external shading devices are nearly the same. Similar results are also capable to the optimum shading schemes regarding the above two materials. As for the aluminum materials, the total CO_2 emission amounts regarding the optimum and base options are higher than those of the other two materials, and the total CO_2 emission amount of its optimum case is 11.48% higher than the base option.

2) Design dimension (volume)

Under the same external shading design dimension (volume of the shading devices), the differences in the total CO_2 emissions of external shading equipment made of the three materials are affected by the density of the material, the replacement frequency of the material within the 50-year life cycle, and the material carbon emission factors. Comparison of the total CO_2 emission amounts with respect to different shading design dimensions indicate that the highest amount regarding the base shading option is Aluminum A, followed by Polycarbonate A and Merbau A. As for the energy-saving optimum case, the total CO_2 emission amount of Aluminum B is the highest, followed by Polycarbonate B and Merbau B.

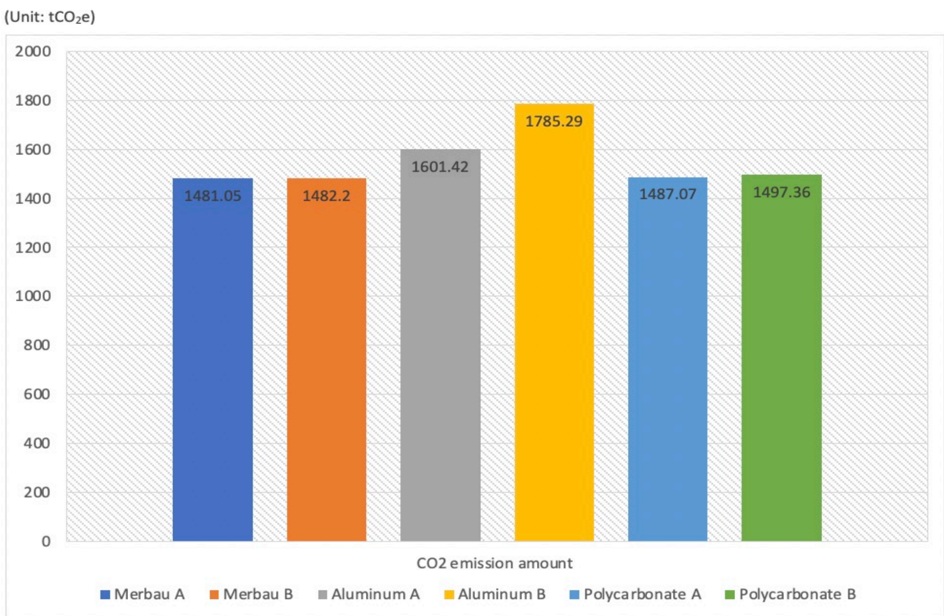


Figure 7.2 Total CO_2 emission amount of building materials production stage (C_{SC}) regarding six proposed fixed external shading devices (50-year building lifespan)

(2) Building materials transportation stage

The CO_2 emission amounts of a variety of construction materials during building materials transportation stage with respect to six proposed fixed external shading devices have been obtained (See Appendix O-T). The amounts of CO_2 emission of different construction materials have been estimated through multiplying the total weight of the materials by transportation distance (default parameters in CEEB system) and corresponding CO_2 emission factors (see Table 7.2). These results are automatically generated by CEEB simulation. By summing up the carbon emission amount of various building materials, the total CO_2 emission amounts of different external shading designs during the transportation stage (C_{YS}) have been estimated. The CO_2 emission amount of reference building at this stage is 81.46 tCO_2e. Figure 7.3 listed the total CO_2 emission amounts of six proposed external shading designs at the building materials transportation stage. The total CO_2 emission amounts regarding six external shading designs at this specific stage from high to low are Merbau B of 82.96 tCO_2e, Aluminum B of 82.38 tCO_2e, Polycarbonate B of 82.18 tCO_2e, Merbau A of 82.06 tCO_2e, Aluminum A of 81.86 tCO_2e, Polycarbonate A of 81.74 tCO_2e. Similar with last section, further discussion is conducted from the perspective of shading materials and external shading design dimension:

1) Shading materials

Through comparison of the total CO_2 emission amounts with respect to different shading materials, the ones regarding the base shading options (among three materials made devices) are nearly the same. Similar results are also capable to the optimum shading schemes regarding the above three materials. As for the merbau made materials, the total CO_2 emission amounts regarding the optimum and base options are slightly higher than those of the other two materials, and the total CO_2 emission amount of its optimum case (Merbau B) is 1.10% higher than the base option (Merbau A). Further, the aluminum made optimum case (Aluminum B) is 0.64% higher than the base option (Aluminum A), and the polycarbonate made optimum case (Polycarbonate B) is 0.54% higher than the base option (Polycarbonate A).

2) Design dimension (volume)

The comparison of the total CO_2 emission amounts with respect to different shading design dimensions (volume) indicates that the highest amount regarding the base shading option is Merbau A, followed by Aluminum A and Polycarbonate A. As for the energy-saving optimum case, the total CO_2 emission amount of Merbau B is the highest, followed by Aluminum B and Polycarbonate B.

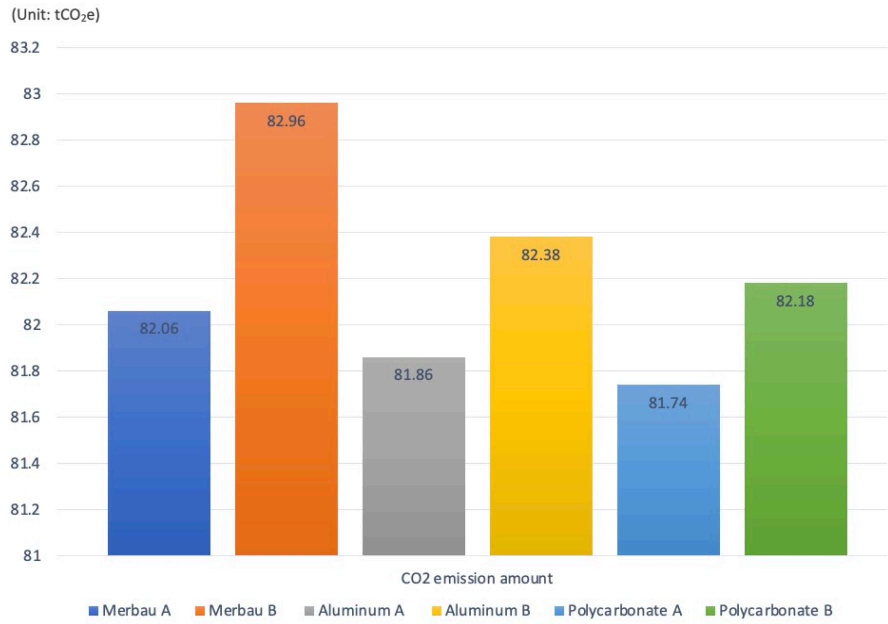


Figure 7.3 CO_2 emission amount of building materials transportation stage (C_{YS}) regarding six proposed fixed external shading device (50-year building lifespan)

7.3.2. Building construction stage

Table 7.5 listed CO_2 emission amount of building construction stage (C_{JZ}). Calculated by equations (7.2) and (7.3), the CO_2 emission amount at this specific stage can be obtained, a total of 10.67 tCO_2 carbon emission amount has been automatically generated by using CEEB.

Table 7.5 CO_2 emissions amount of building construction stage (C_{JZ}) (50-year building lifespan)

Construction area (A) (m^2)	**Number of above-ground layers (X)**	**Carbon emission amount per unit area (Y) ($kgCO_2/m^2$)**	**Carbon emission amount during building construction stage (C_{JZ}) (tCO_2)**
2,138.25	3	4.99	10.67

(Source: CEEB 2024 database.)

7.3.3. Carbon sink of buildings

Table 7.6 listed the fixed amount of CO_2 emissions of building carbon sink (Cp) in 50 years building lifespan. Calculated by equation (7.5), the fixed amount of CO_2 emission each year can be obtained. Then multiplying by 50, the building carbon sink over the 50-year building life cycle (Cp) can be estimated. These results are automatically generated by the CEEB simulation. The fixed carbon emission amount for this specific stage is divided into the following two parts:

(1) Tall grass flower beds or tall grass fields. The fixed amount of carbon emissions of this part is 67.28 tCO_2.
(2) Grass flower bed, natural wild grass, lawn, aquatic plants. The fixed amount of carbon emissions of this part is 15.61 tCO_2.

A total of 82.89 tCO_2 of fixed carbon emission amount in 50-year life cycle has been estimated by using CEEB.

Table 7.6 Fixed amount of CO_2 emissions of building carbon sink (Cp) (50-year building lifespan)

Plant	Carbo sink factor (Q_i) (kg/m^2·a)	Area ($\|C_i\|$) (m^2)	Lifespan	Fixed amount of carbon emissions (tCO_2)
Tall grass flower beds or tall grass fields (height about 1.0m, soil depth >0.3m)	1.15	1,170.03	50	67.28
Grass flower bed, natural wild grass, lawn, aquatic plants	0.50	624.53	50	15.61
Cp				82.89

(Source: CEEB database.)

7.3.4. Building operation stage

The CO_2 emission amounts at building operation stage regarding the six proposed fixed external shading devices have been obtained, which automatically generated by CEEB (see Appendix U-Z). As mentioned in section 7.3.3, power consumption is mainly composed of cooling systems, air conditioning fans and lighting systems (see Table 7.4). Calculated by equation (7.4), the annual CO_2 emission amount of power consumption (C_M) is obtained. The respective CO_2 emission amounts in 50-year lifespan regarding six cases have been determined through multiplying the values of C_M by 50. The CO_2 emission amount at this specific stage is calculated by 'CO_2 emission amount of power consumption' (sum of C_M) minus 'fixed amount of carbon sink' (sum of Cp).

Under the same external shading design dimension, Figure 7.4 shows that the CO_2 emission amounts for the three shading materials are consistent. This indicates that the variation of CO_2 emission amount is irrelevant to the type of shading material in this specific stage. Under the same shading material condition, the optimum shading case has a carbon emission reduction of 0.42% compared with the basic option, showing the correlation between CO_2 emission amount and external shading dimension. Using the merbau made case as an example, it can be seen from the value in Appendix U and Appendix V that only the power consumption of cooling system can make an impact on the changes of CO_2 emission amount. This infers that the longer the fixed external shading protrusion, the lower the annual power consumption of the cooling system, resulting in lower CO_2 emissions at this stage. As for the reference building, the CO_2 emission amount at this stage is 4,287.61 tCO_2.

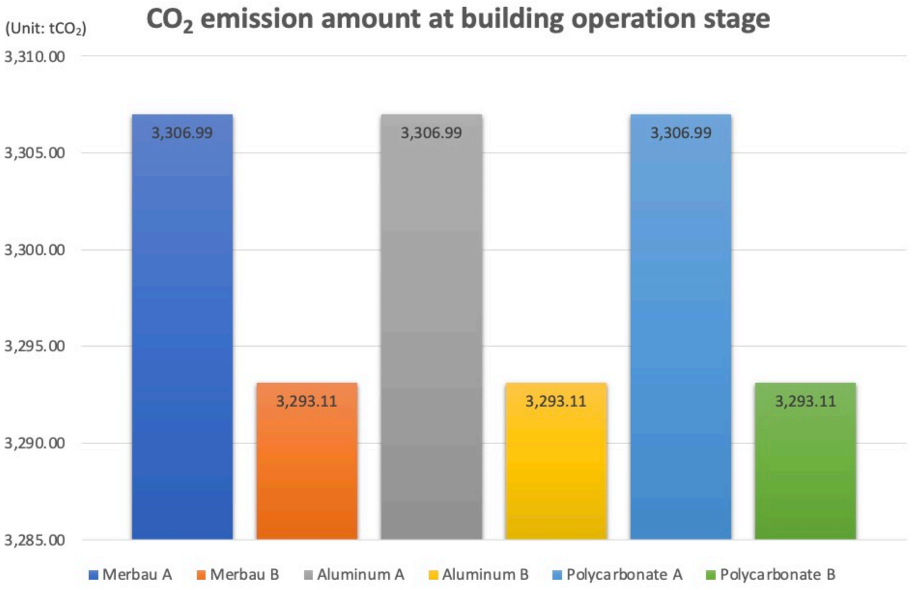


Figure 7.4 Total CO_2 emission amount at building operation stage regarding the six proposed fixed external shading devices (50-year building lifespan)

7.3.5. Building demolition stage

Table 7.7 listed CO_2 emission amount of building demolition stage (C_{CC}). By using the empirical formula method and verified by equations (7.2) and (7.3), the CO_2 emission amount at this specific stage can be estimated, a total of 10.67 tCO_2 carbon emission amount has been automatically generated by using CEEB.

Table 7.7 CO_2 emission amount at the building demolition stage (C_{CC}) (50-year building lifespan)

Construction area (A) (m^2)	**Number of above-ground layers (X)**	**Carbon emission amount per unit area (Y) ($kgCO_2/m^2$)**	**Carbon emissions during demolition phase (CCC) (tCO_2)**
2,138.25	3	4.99	10.67

(Source: CEEB 2024 database.)

7.3.6. Estimation of life cycle carbon emission amount

As mentioned above, four main stages are included in $LCCO_2$ emission, e.g., 1) building materials production and transportation stage, 2) building construction stage, 3) building operation stage, and 4) building demolition stage. Calculated by equation (7.6), $LCCO_2$ emission amounts of the six proposed external shading cases have been estimated by summing up the respective CO_2 emission amounts of four building stages. As listed in Table 7.8, the $LCCO_2$ emission amounts regarding six shading cases from high to low are Aluminum B of 5,182.12 tCO_2, Aluminum A of 5,011.61 tCO_2, Polycarbonate A of 4,897.14 tCO_2, Polycarbonate B of 4,893.99 tCO_2, Merbau A of 4,891.44 tCO_2, and Merbau B of 4,879.61 tCO_2. Compare with the $LCCO_2$ emission amount of the reference building, the ones of the six studied fixed external shading designs are reduced by 11.76%, 14.63%, 16.58%, 16.64%, 16.69%, 16.90% respectively, with respect to Aluminum B, Aluminum A, Polycarbonate A, Polycarbonate B, Merbau A, and Merbau B.

Table 7.8 and Figure 7.5 highlight the simulation results for the four building stages. The CO_2 emission amount at the building operation stage accounts for the largest proportion of $LCCO_2$, which is approximately 65%, followed by the ones at the production and transportation stage of building materials, accounting for approximately 35%. The lowest proportion is the CO_2 emission amount at the building construction stage and building demolition stage, accounting for less than 0.3% respectively, which can be ignored.

The results shows that the CO_2 emission amount in the operation phase of the building have a significant impact on the CO_2 emission in the life cycle of the building, mainly reflected in the fact that the protrusion length of the fixed external shading devices affecting the annual power consumption of the cooling system, and thus have an influence on its total CO_2 emission amount. In addition, the CO_2 emission amounts in the building construction stage and the building demolition stage are fixed values, with the figure of 10.67 tCO_2. This is because the CO_2 emission amounts in the above two stages are both estimated by using the empirical formula method (see equations 7.2 and 7.3), which is currently being adopted in the green building assessment practice. However, the materials' impact on CO_2 emission is worth further investigation in the future work.

Table 7.8 Life cycle CO_2 emission regarding six proposed fixed external shading devices (tCO_2) (50-year building lifespan)

	Unit	**Reference building**	**Merbau A**	**Merbau B**	**Aluminum A**	**Aluminum B**	**Polycarbonate A**	**Polycarbonate B**
CO_2 emission amount of building materials production stage（C_{SC}）	tCO_2e	1,480.29	1,481.05	1,482.20	1,601.42	1,785.29	1,487.07	1,497.36
CO_2 emission amount of building materials transportation stage (C_{YS})	tCO_2e	81.46	82.06	82.96	81.86	82.38	81.74	82.18
CO_2 emission amount of building materials production and transportation stage (C_{JC}*A)	**tCO_2e**	**1,561.75 (26.60%)**	**1,563.11 (31.96%)**	**1,565.16 (32.08%)**	**1,683.28 (33.59%)**	**1,867.67 (36.04%)**	**1,568.81 (32.04%)**	**1579.54 (32.28%)**
CO_2 emission amount of building construction stage (C_{JZ})	**tCO_2**	**10.67 (0.18%)**	**10.67 (0.22%)**	**10.67 (0.22%)**	**10.67 (0.21%)**	**10.67 (0.21%)**	**10.67 (0.22%)**	**10.67 (0.22%)**
CO_2 emission amount of power consumption (C_M)	tCO_2	4,370.50	3,389.88	3,376.00	3,389.88	3,376.00	3,389.88	3,376.00
(-) Fixed amount of carbon sink (Cp)	tCO_2	82.89	82.89	82.89	82.89	82.89	82.89	82.89
CO_2 emission amount of building operation stage	**tCO_2**	**4,287.61 (73.04%)**	**3,306.99 (67.60%)**	**3,293.11 (67.48%)**	**3,306.99 (65.99%)**	**3,293.11 (63.54%)**	**3,306.99 (67.52%)**	**3,293.11 (67.28%)**
CO_2 emission amount of building demolition stage (C_{CC})	**tCO_2**	**10.67 (0.18%)**	**10.67 (0.22%)**	**10.67 (0.22%)**	**10.67 (0.21%)**	**10.67 (0.21%)**	**10.67 (0.22%)**	**10.67 (0.22%)**
$LCCO_2$ emission amount	**tCO_2**	**5,870.70**	**4,891.44**	**4,879.61**	**5,011.61**	**5,182.12**	**4,897.14**	**4,893.99**

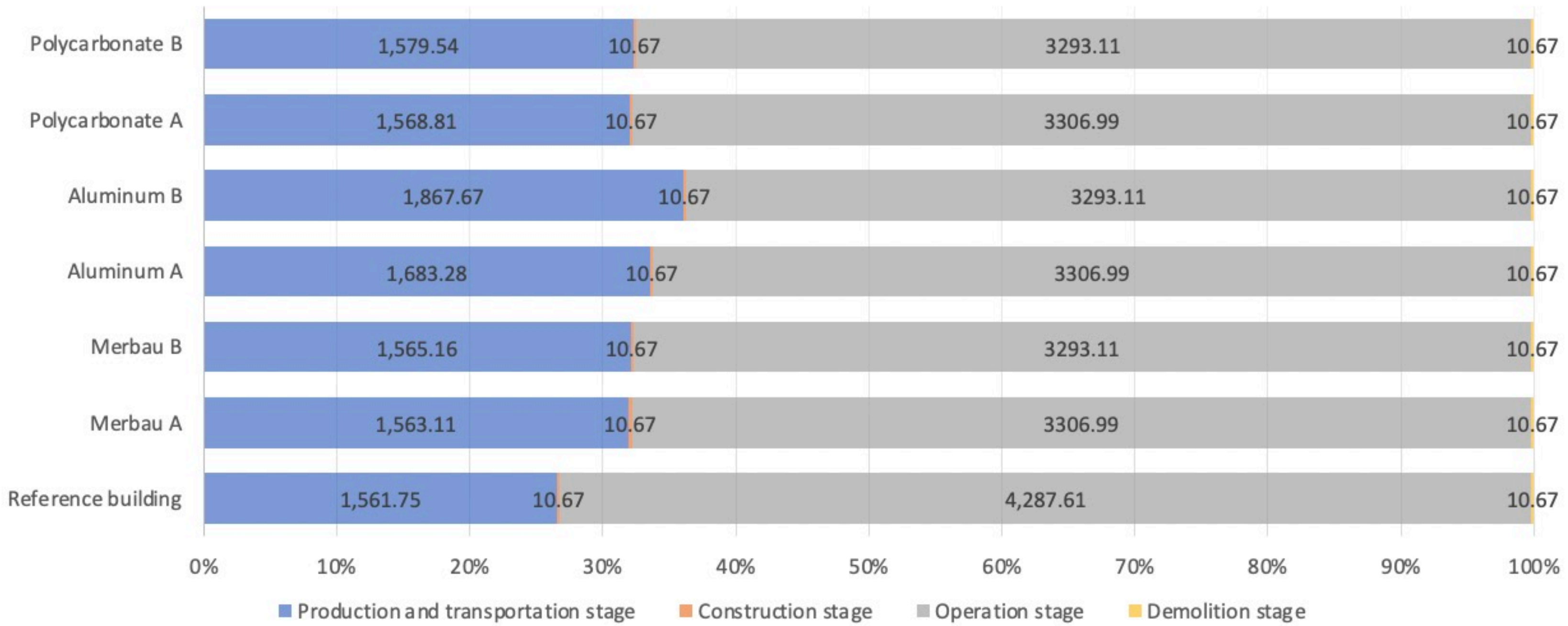


Figure 7.5 $LCCO_2$ emission amount of six proposed fixed external shading device (50-year building lifespan)

7.4. Discussion and inferences

Over the building life cycle of 50 years, different building materials produce various carbon emission amounts. This part of research mainly focuses on the differences in CO_2 emission amounts generated by a choice of six fixed external shading devices at different building stages, in terms of shading materials and shading devices dimension. Further discussions will be conducted as follow:

7.4.1. Materials and dimension of fixed external shading devices

1) As for the Merbau made materials, the building with Merbau A shading strategy emits 4,891.44 tCO_2 carbon emission amount, with average emission amount of 97.83 tCO_2/year (45.75 kg CO_2/m^2/year). The building with Merbau B shading strategy emits 4,879.61 tCO_2 carbon emission amount, with average emission amount of 97.59 tCO_2/year (45.64 kg CO_2/m^2/year). The total $LCCO_2$ emission amount of the optimum case (Merbau B) is 0.24% lower than the base one (Merbau A).

2) As for the Aluminum made materials, the building with Aluminum A shading strategy emits 5,011.61 tCO_2 carbon emission amount, with average emission amount of 100.23 tCO_2 (46.88 kg CO_2/m^2/year). The building with Aluminum B shading strategy emits 5,182.12 tCO_2 carbon emission amount, with average emission amount of 103.64 tCO_2/year (48.47 kg CO_2/m^2/year). The total $LCCO_2$ emission amount of the optimum case (Aluminum B) is 3.04% higher than the base one (Aluminum A).

3) As for Polycarbonate made materials, the building with Polycarbonate A strategy emits 4,897.14 tCO_2 carbon emission amount, with average emission amount of 97.94 tCO_2/year (45.81 kg CO_2/m^2/year). The building with Polycarbonate B strategy emits 4,893.99 tCO_2 carbon emission amount, with average emission amount of 97.88 tCO_2/year (45.78 kg CO_2/m^2/year). The total $LCCO_2$ emissions of the optimum case (Polycarbonate B) is 0.06% lower than the base one (Polycarbonate A).

7.4.2. Contribution of different building stages on carbon emissions

For a certain shading material, the carbon emission amounts generated by the building during different building stages made various contribution to the $LCCO_2$ emission of the building.

1) In terms of merbau made shading materials for the optimum case (Merbau B), the building operation stage contributes the most (67.48%) to the total $LCCO_2$ emissions, followed by the building material production and transportation stage (32.08%), building construction stage (0.22%), and building demolition stage (0.22%).
2) In terms of aluminum made shading materials for the optimum case (Aluminum B), the building operation stage contributes the most (63.54%) to the total $LCCO_2$ emissions, followed by the building material production and transportation stage (36.04%), building construction stage (0.21%), and building demolition stage (0.21%).
3) In terms of polycarbonate made shading materials for the optimum case (Polycarbonate B), the building operation stage contributes the most (67.28%) to the total $LCCO_2$ emissions, followed by the building material production and transportation stage (32.28%)~~,~~ building construction stage (0.22%), and building demolition stage (0.22%).

From the perspective of the entire building life cycle, amongst the six fixed external shading designs, it can be inferred that Merbau B has the lowest total carbon emission amount through simulation by CEEB 2024.

7.5. Summary

This chapter presents a case study to demonstrate the use of the proposed building carbon emission simulation system named CEEB 2024. This system has been in practical use in Chinese construction industry. Six fixed external shading design options of a three-storey green educational building in Shenzhen have been assessed, in order to illustrate their carbon emission impact. For the environmental aspect carbon emission estimation, the life cycle boundary and recycled content for building materials are specified as cradle to gate and Chinese averages. The building plan area (2,138.25 m^2) and corresponding carbon emission factors are required for carbon emission calculations. Various contributions of the construction materials to the carbon emission of the overall building structure can be known from the aforementioned tables and charts. Simulation results demonstrate the $LCCO_2$ emission amounts in 50-year lifespan from high to low, namely Aluminum B (5,182.12 tCO_2), Aluminum A (5,011.61 tCO_2), Polycarbonate A (4,897.14 tCO_2), Polycarbonate B (4,893.99 tCO_2), Merbau A (4,891.44 tCO_2), and Merbau B (4,879.61 tCO_2). The conversion to annual carbon emission amounts is 48.47 kg CO_2/m^2/year, 46.88 kg CO_2/m^2/year, 45.81 kg CO_2/m^2/year, 45.78 kg CO_2/m^2/year, 45.75 kg CO_2/m^2/year, and 45.64 kg CO_2/m^2/year respectively. This aspect of the research aims to apply the environmental assessment method on a case study as evidence of its effectiveness, which is further substantiated by the multi-criteria evaluation process presented in Chapter 8.

Chapter 8. Multi-criteria Decision Analysis (MCDA)

This chapter proposes a multi-criteria assessment method named MCDA to determine an optimum fixed external shading solution for the studied green educational building. Six fixed external shading alternatives and three specific criteria have been determined through analysis results from the past few chapters. The entropy weight and ELECTRE I methods are applied. A series of formula calculation and XLSTAT 2022 plug-in based on ELECTRE I method are performed in Excel spreadsheet. A priority ranking table for the six shading solutions is generated. It covers a prototype evaluation, which aims to provide information on the sustainability of building external shading solutions in the conceptual design activities for building energy efficiency structural engineers. This is also to provide the stakeholders with considerable decision-making advice related to the generation of appropriate shading strategy. The assessment method has been found to be appropriate as the research objectives are clear. New information about the assessment method will be generated, and the feedback can be used to improve the green building assessment in specific Chinese cases. The category of MCDA and ELECTRE method, assessment process, assessment results, and corresponding discussions and implications are presented.

8.1. Category of MCDA and ELECTRE method

8.1.1. Category of MCDA

The Multi-criteria decision analysis (MCDA) techniques aim to evaluate alternatives based on multiple criteria by using the systemic analysis. This is to support decision making in different problems and identify the best choice among a set of alternatives. MCDA methods provide decision makers with different decision suggestions, including ranking, sorting, selecting, and clustering alternatives (e.g., technologies or scenarios) under scientific assessment. A variety of data types and preferences can be dealt with by MCDA, guiding decision makers to make appropriate decisions (Cinelli *et al*., 2022). There are many different MCDA methods that can be used to appraise the sustainable performance of building envelopes. MCDA methods are based on the different theoretical foundations such as optimization, goal aspiration, utility function, outranking. Prominent among them is Scoring Multi-Attribute Analysis (Hereinafter referred to as SMAA), Multi Attribute Utility Theory (Hereinafter referred to as MAUT), Linear Programming (Hereinafter referred to as LP), Cluster Analysis (Hereinafter referred to as CA), Multivariate Discriminant Analysis (Hereinafter referred to as MDA), Weighted Sum Method (Hereinafter referred to as WSM), Weighted Product Method (Hereinafter referred to as WPM), Technique for Order Preference by Similarity to Idea Solution (Hereinafter referred to as TOPSIS), ÉLimination Et Choix Traduisant la REalité (ELECTRE), Evaluation of Mixed Data (Hereinafter referred to as EVAMIX), Complex Proportional Assessment (Hereinafter referred to as COPRAS), the Analytical Hierarchy Process (AHP), Choquet Integral, PROMETHEE, VIKOR, and MIVES.

8.1.2. ELECTRE method

ELECTRE method deals with the outranking relationship by using pairwise comparison among the alternatives under each of the appropriate criteria separately. An alternative is considered better than the others if it satisfies one or more criteria, as well as equal to the remaining ones (compared with the specific criteria regarding other alternatives). Scholar Roy introduced a ranking relationship between two alternatives $\boldsymbol{A_k}$ from $\boldsymbol{A_l}$, which can be applied in the subsequent study (Sri *et al.*, 2006; English pesunalum Tamilan da, 2017). Traditionally speaking, the ELECTRE method can be calculated by a series of formulas to determine the outranking relationship between alternatives (Rocha, 2023). All ELECTRE methods belong to the family of outranking methods, one of the classic families of methods within MCDA. There are several specific features in ELECTRE that distinguish them from other MCDA methods:

- They compare alternatives pairwise by testing a hypothesis that one hypothesis is at least as good as another.
- Based on these comparisons, ELECTRE methods can provide various types of results.

These methods are known to handle information carefully. The cardinality of the used numbers is not a prerequisite and cannot be guaranteed in most cases. Pairwise comparison of alternatives allows considering incomparability. ELECTRE family includes ELECTRE I, ELECTRE Iv, ELECTRE II, ELECTRE III, ELECTRE IV, ELECTRE TRI, ELECTRE IS, ELECTRE TRI-C, ELECTRE TRI-nC. Their corresponding characteristics are listed in Table 8.1.

Table 8.1 Characteristics of ELECTRE methods

Type of ELECTRE method	Type of MCDA problem	Approach	Thresholds	Criteria	Weight
ELECTRE I	Choice problematic or problematic α	select a smallest set of best alternatives	-	not consider pseudo-criteria (True criteria)	use criteria weight
ELECTRE Iv	choice problematic or problematic α	select a smallest set of best alternatives	consider veto thresholds	not consider pseudo-criteria (True criteria)	use criteria weight
ELECTRE II	ranking problematic or problematic γ	construct an ordering of the alternatives from the best to the worst	-	not consider pseudo-criteria (True criteria)	use criteria weight
ELECTRE III	ranking problematic or problematic γ	construct an ordering of the alternatives from the best to the worst	-	Use pseudo-criteria	use criteria weight
ELECTRE IV	ranking problematic or problematic γ	construct an ordering of the alternatives from the best to the worst	-	Use pseudo-criteria	Not use criteria weight
ELECTRE TRI	sorting problematic or problematic β	assign alternatives to a set of pre-defined categories	-	Use pseudo-criteria	use criteria weight
ELECTRE IS	choice problematic or problematic α	select a smallest set of best alternatives	-	Use pseudo-criteria	use criteria weight
ELECTRE TRI-C	sorting problematic or problematic β	assign alternatives to a set of pre-defined categories	-	Use pseudo-criteria	use criteria weight
ELECTRE TRI-nC	sorting problematic or problematic β	assign alternatives to a set of pre-defined categories	-	-	-

Among the above ELECTRE methods, ELECTRE I is used to identify a set of solutions to a decision-making problem, which is suitable for this research with the aim of generating a preferred choice among a small set of alternatives. To do this, concordance matrix and discordance matrix are generated for aggregation into outranking matrix. Based on the outranking matrix, the final ranking table can be generated.

8.2. Assessment process by ELECTRE I method

Before conducting ELECTRE I method to assess the six proposed fixed external shading devices on three identified criteria for the studied green educational building, the entropy weight method is adopted to determine the respective weight coefficients. Detailed assessment process can be divided into the following two parts.

8.2.1. Weight coefficients determination based on entropy weight method

Weight of each criteria is necessary to be determined before conducting assessment by using assessment model, to reflect the importance of each criteria. Weight can be calculated by various methods. AHP (Analytic hierarchy process) and entropy weight method are the mainstream. As a kind subjective weighting method, experts or decision makers adopt AHP method to rank the importance of each criteria based on their actual experience and determine their final weights. This simple method is capable to assign weights to indicators without actual data. However, it is greatly influenced by experts or decision makers due to its subjectivity. In contrast, the entropy weight method is a kind of objective weighting method, which mainly assigns weights objectively based on the variation degree of the indicators, rather than relying on expert experience. This can avoid subjective evaluation bias. The values of building's heating and cooling energy consumption, power consumption, material costs and CO_2 emission amounts in this whole research project are based on specific and objective data support. Therefore, the entropy weight method is adopted.

(1) Basic principle of entropy weight method

First proposed by Rudolf Clausius (Li *et al.*, 2021), the concept of entropy came from thermodynamics in physics, then developed into statistical physics, indicating the degree of irregular arrangement between particles. Shannon (1948) introduced entropy into information theory, using entropy to represent the uncertainty of things. The accuracy and reliability of decision-making are largely affected by the quantity and quality of the obtained information. The greater the amount of information, the smaller the uncertainty and the entropy value. In other words, the smaller the entropy value, the more useful information the criteria provides and the greater the criteria weight. Therefore, when making specific decisions, weights can be calculated based on the variation degree of each criteria. This is the entropy of the criteria.

Assuming that a random experiment A has a total of m random events. There will be n possible independent results m_1, m_2..., m_n, and the corresponding probabilities of occurrence are P_1, P_2..., P_n, which meet the following equation (8.1) (Shen, 2019):

$$0 \leq P_i \leq 1 (i = 1, \dots, n) \ \sum_{i=1}^{n} P_i = 1 \tag{8.1}$$

A major feature of random events is that there is a great deal of uncertainty in the occurrence of a particular event. Therefore, probability experiments are needed to detect the rule of event occurrence. (Shannon, 1948) further introduced the function H_n to characterize the uncertainty of random experiments, as listed in the equation (8.2) (Shen, 2019):

$$H_n = H(P_1, P_2, \dots, P_n) = -k \sum_{i=1}^{n} P_i \, LnP_i \tag{8.2}$$

where k represents a constant greater than 0. $\mathrm{H_n}$ represents the result uncertainty of a random event. When $\mathrm{H_n} \geq 0$, it is called information entropy. The minimum value of $\mathrm{H_n}$ is 0, only if there is only one random event result $\mathrm{P_i} = 1$, then the rest of the probabilities are 0. The maximum value of $\mathrm{H_n}$ is $k\, Ln\, n$, only if the probability of all event results is equal, that is, $\mathrm{P_i} = 1/\mathrm{n}$. Information entropy is the basis of the entropy weight method. Through this value, the degree of information confusion can be evaluated and the weight of each criteria can be determined.

(2) Calculation steps of entropy weight method

Entropy weight method can be used to quantify and integrate multiple criteria for decision-making. The specific steps of calculating weights by using entropy weight method are presented as follows (Shen, 2019; Li *et al.*, 2021).

Step 1: Standardization of criteria

Assuming that there are m evaluation alternatives and n attribute evaluation criteria, all the data are constructed into a joint decision evaluation matrix A (equation 8.3). Among them, x_{ij} is the i-th evaluation alternative parameter of the j-th criteria:

$$A = \begin{bmatrix} x_{11} & \cdots & x_{1j} \\ \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} \end{bmatrix} \tag{8.3}$$

In order to eliminate the differences of dimension and unit among the data set, the data x_{ij} in the above matrix A is to be standardized by the deviation standardization method. y_{ij} is the standardized value, which can be calculated by equation (8.4):

$$y_{ij} = \frac{x_{ij} - min(X_i)}{max(X_i) - min(X_i)} \tag{8.4}$$

Matrix $Y = \left[y_{ij}\right]_{m*n}$ is a standardized matrix, and $y_{ij} \in [0,1]$. m refers to the number of alternatives, whilst n refers to the number of criteria. Then the matrix Y is needed to be normalized to obtain the specific gravity matrix P. The specific gravity P_{ij} of the i-th alternative on the j-th criteria component can be calculated by equation (8.5):

$$P_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}} \tag{8.5}$$

Step 2: Calculation of the criteria weight using the entropy weight method

According to the equation (8.2) of H_n, the entropy value e_j of the j-th criteria component can be calculated by equation (8.6):

$$e_j = -k \sum_{i=1}^{m} P_{ij} \, Ln\left(P_{ij}\right) \tag{8.6}$$

where $k = \frac{1}{lnm}$.

After calculating the entropy value e_j, the final weights can be generated by performing normalization. The difference coefficient $g_j$of the j-th criteria component can be calculated by equation (8.7):

$$g_j = 1 - e_j \tag{8.7}$$

Finally, the weight coefficient ω_j of the j-th criteria component can be calculated by equation (8.8):

$$\omega_j = \frac{g_j}{\sum_{j=1}^{n} g_j} \tag{8.8}$$

Matrix $W = \left[\omega_j\right]_{1*n}$ is the final weight matrix of all the criteria, where $\omega_j \in [0,1]$, $\sum_{j=1}^{n} \omega_j$=1. Characteristics of the entropy weight can be listed as follow:

1) The maximum value of the entropy weight is 1, while the minimum value is 0. When the entropy value e_j is 1, the entropy weight ω_j is 0. That is, the values of P_{ij} are the same, which means that there is no difference between a certain criteria value of all the alternatives, providing invalid information for decision-making. Therefore, this criteria should be eliminated.

2) Similarly, the larger the entropy value, the smaller the entropy weight, indicating the usefulness of the criteria. On the contrary, this criteria needs to be considered as the focus.

8.2.2. Multi-criteria decision assessment by ELECTRE I method

In order to simplify and reduce errors in the calculation process, the XLSTAT 2022 plug-in of Excel is applied in this part of research to support the MCDA calculations (XLSTAT, 2024a). Both the equation calculation and plug-in usage process will be illustrated in the following two parts.

(1) ELECTRE

There are two main stages in most of the ELECTRE methods. The first stage is to construct the outranking relations of alternatives. The second stage is to apply these outranking relations to generate their final ranking. In addition, ELECTRE can construct one or more outranking relations, e.g., crispy, fuzzy, or embedded (Liu and Wan, 2019). Seven steps of this method are as follows (Hartati *et al*., 2010; Özmen and Demir, 2023):

Step 1: Create decision matrix A

Decision matrix A has been generated by equation (8.3), including alternatives and criteria.

Step 2: Calculate the standard decision matrix R

There is a need to perform pairwise comparison of the criteria regarding each alternative listed in equation (8.3) of the decision matrix A. The values of x_{ij} are normalized through comparison into a scale by equation (8.9), to create the standard decision matrix R:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} {x^2}_{ij}}}, i = 1,2, \dots, m \; and \; j = 1,2, \dots, n \tag{8.9}$$

Step 3: Create the weighted standard decision matrix V

The importance factor (also referred to weight coefficient ω_j) has been assigned to each criteria through calculation by the aforementioned entropy weight method, representing as the relative importance. The weighted standard decision matrix V is then generated through multiplying the weight coefficient ω_j by the normalized value r_{ij} for the subsequent pairwise comparison (as seen in equation 8.10).

$$V_{ij} = \begin{bmatrix} \omega_1 r_{11} & \cdots & \omega_j r_{1j} \\ \vdots & \ddots & \vdots \\ \omega_i r_{i1} & \cdots & \omega_j r_{ij} \end{bmatrix} \tag{8.10}$$

Step 4: Determine the concordance and discordance sets

Matrix V is used to determine the concordance set $\{C_{kl}\}$ and discordance set $\{D_{kl}\}$. The alternatives are compared with each other regarding each criteria. The sets of $\{C_{kl}\}$ and $\{D_{kl}\}$ can be determined by equations (8.11) and (8.12).

$$C_{kl} = \{j \mid v_{kj} \geq v_{lj}\}, j = 1,2,\dots,n \tag{8.11}$$

$$D_{kl} = \{j \mid v_{kj} < v_{lj}\}, j = 1,2,\dots,n. \tag{8.12}$$

Step 5: Create the concordance matrix C and discordance matrix D

The concordance matrix C contains the elements associated with the sum of weights regarding the criteria when calculating the concordance index, which means that alternative A_k is preferred over alternative A_l $(k, l = 1,2,\dots,m)$. Both of the matrix C and D is in size of m*m, and it does not take the value when k is equal to 1. The elements of these two matrices are respectively calculated by equations (8.13) and (8.14).

$$c_{kl} = \sum_{j \in C_{kl}} \omega_j \tag{8.13}$$

$$d_{kl} = \frac{\max\limits_{j \in d_{kl}} |v_{kj} - v_{lj}|}{\max\limits_{j} |v_{kj} - v_{lj}|} \tag{8.14}$$

Step 6: Construct the concordance-dominance matrix F and the discordance-dominance matrix G

The size of the concordance-dominance matrix F is m*m. Through comparing the concordance threshold value with the elements in the concordance matrix, the matrix G is constructed. The concordance threshold value c can be calculated by equation (8.15).

$$\underline{c} = \frac{\sum_{k=1}^{m} \sum_{l=1}^{m} c_{kl}}{m(m-1)} \tag{8.15}$$

If the concordance index exceeds the threshold value c, the alternative A_k has a chance to dominate the alternative A_l:

$$c_{kl} \geq \underline{c} \tag{8.16}$$

The elements of the matrix F take on binary values 1 or 0, while the elements on the diagonal of the matrix have no value, representing the same alternatives. The remaining elements of matrix F are determined by equation (8.17).

$$f_{kl} = \begin{cases} 1, & c_{kl} \geq \underline{c} \\ 0, & c_{kl} < \underline{c} \end{cases} \tag{8.17}$$

The size of the discordance-dominance matrix G is m*m. Through comparing the discordance threshold value with the elements in the discordance matrix, the matrix F is constructed. The discordance threshold value d can be calculated by equation (8.18).

$$\underline{d} = \frac{\sum_{k=1}^{m} \sum_{l=1}^{m} d_{kl}}{m(m-1)} \tag{8.18}$$

The elements of the matrix G take on binary values 1 or 0, while the elements on the diagonal of the matrix have no value, representing the same alternatives. The remaining elements of matrix G are determined by equation (8.19).

$$g_{kl} = \begin{cases} 1, & d_{kl} \geq \underline{d} \\ 0, & d_{kl} < \underline{d} \end{cases} \tag{8.19}$$

Step 7: Create the aggregate dominance matrix E

In order to clarify the dominance of matrix E, there needs to be an aggregate taking for the concordance-dominance matrix F and discordance-dominance matrix G, representing the partial preference order of alternatives. The elements of matrix E is calculated by equation (8.20).

$$e_{kl} = f_{kl} * g_{kl} \tag{8.20}$$

Then the final matrix E is constructed as follows:

$$E_{ij} = \begin{bmatrix} f_{11}g_{11} & \cdots & f_{1j}g_{1j} \\ \vdots & \ddots & \vdots \\ f_{i1}g_{i1} & \cdots & f_{ij}g_{ij} \end{bmatrix} \tag{8.21}$$

If $e_{kl} = 1$, it means that alternative A_k is preferred over alternative A_l.

The larger the concordance index and the smaller the discordance index, the greater the dominance relationship of one alternative over the other. The optimum alternative set can be determined through evaluating the outranking relationship by adopting the minimum concordance and discordance thresholds. The set of all the alternatives that rank higher contains the best alternative in problem-solving. The reference threshold needs to be altered if the obtained alternative set is very small or empty, since an alternative has a concordance index over its concordance threshold, and a discordance index below its discordance threshold. This means that one alternative outranks another. Likewise, the reference threshold is to be changed to reduce the number of alternatives when the set of alternatives is large (Yoon and Hwang, 1995; Rocha, 2023).

(2) ELECTRE I calculation process by XLSTAT 2022

Since the problem of data errors and time-consuming may exist when carrying out the assessment of ELECTRE method by using the above formula calculation. This part of research will adopt XLSTAT 2022 plug-in to automatically conduct multi-criteria decision assessment regarding ELECTRE I. Another reason for choosing XLSTAT to conduct automatic calculation of ELECTRE I is that there is no clue to identify the concordance and discordance thresholds for the studied criteria, and the default values of reference thresholds have been set in XLSTAT system. The thresholds can be left unchanged if there are no specific requirements (XLSTAT, 2024a). By constructing an outranking relation, the ELECTRE I approach has the strength to establish pairwise relationships between possible alternatives to determine concordance and discordance matrix. Let a and b be two potential alternatives, ELECTRE I give an over ranking matrix that numerically translates the assertions "a over ranks b", noted aSb, meaning that the alternative a is privileged over the alternative b and the opposite assertion.

XLSTAT is a powerful and flexible add-on for data analysis in Microsoft Excel (XLSTAT, 2024b). This easy-to-use plug-in is currently widely used in various area of data analysis, e.g., data management, descriptive statistics, data visualization, modeling data, hypothesis testing, machine learning, sensory analysis, etc. As a subcategory of decision aid, only a small number of studies have adopted XLSTAT for ELECTRE analysis. This includes XLSTAT 2014 for sensory analysis of instant hot chocolate beverage (Dogan et al., 2016), XLSTAT 2019 for office layout evaluation (Eraslan *et al*., 2020), sustainable urban public transport systems assessment by ELECTRE-TRI (Romero-Ania *et al*., 2021) and XLSTAT 2020 for risk assessment analysis regarding COVID-19 transmission (Özmen and Demir, 2023). It has not yet been applied in the construction area and it is worth exploring its research and application value. Through running the procedure of XLSTAT, four main tables will be generated, such as the concordance matrix, discordance matrix, outranking matrix, and final ranking table. The operation process includes the following three steps:

Step 1: Input the value of alternatives and criteria to be assessed.
Step 2: Select the XLSTAT/Marketing/Decision Aid/ELECTRE command.
Step 3: Set the general functions on the ELECTRE dialog box, e.g.,
1) Select the data corresponding to the evaluation of the alternatives over criteria in the Performance matrix field.
2) Select the column that contains the weights in the field with Criteria weights.
3) Select method choice as 'ELECTRE I'.
4) Select the column that contains the Criteria in the field with Row labels.
5) The threshold is the parameter value automatically set by the system, concordance threshold is 1, discordance threshold is 0.
6) Output the table of descriptive statistics, concordance matrix, discordance matrix, outranking matrix, ranking table and sensitivity analysis by automatic computations. The detailed discussion, with respective to the case of fixed external shading devices for the studied educational building will be illustrated in the next section.

8.3. Assessment results regarding the fixed external shading devices

This section will present the assessment results by adopting entropy weight method and ELECTRE I method, including decision matrix construction, weight coefficient determination and application of ELECTRE I.

8.3.1. Construction of decision matrix A

As shown in Figure 8.1, the data represent the assessment of six external shading design on three criteria for generating an optimum shading alternative for the studied educational building within hot summer and warm winter climate of China. The data set collected from the analysis results of the past three chapters is summarized in the performance table. External shading alternatives are presented in columns and criteria in rows. The assessed alternatives are Merbau A, Merbau B, Aluminum A, Aluminum B, Polycarbonate A, and Polycarbonate B, represented as A_1, A_2, A_3, A_4, A_5, A_6 in Table 8.2 respectively. The assessed criteria are the 'energy-saving rate of building envelope' (Φ_{ENV}) (%), the 'net present value of life cycle cost' regarding shading devices (LCC) (k£), the 'life cycle carbon emission amount of building' ($LCCO_2$) (kg CO_2/m^2/year), represented as C_1, C_2, C_3 in Table 8.2. To facilitate the subsequent calculation of weight coefficients and ELECTRE I analysis, the values of six alternatives on three criteria have been constructed in decision matrix A (see Table 8.2).

	A	B	C	D	E	F	G
1	**Criteria**	**Alternative**					
2		Merbau A	Merbau B	Aluminum A	Aluminum B	Polycarbonate A	Polycarbonate B
3	Energy-saving rate of building envelope (ΦENV) (%)	5.27	6.03	5.27	6.03	5.27	6.03
4	NPV(LCC)(k £)	-53.01	-44.31	-38.6	-8.49	-54.61	-48.36
5	LCCO2 (kg CO2/m2/year)	45.75	45.64	46.88	48.47	45.81	45.78

Figure 8.1 Screenshot of performance table regarding six external shading alternatives on three criteria for the studied educational building

Table 8.2 Decision matrix A regarding six shading alternatives on three criteria for the studied educational building

	C_1	C_2	C_3
A_1	5.27	-53.01	45.75
A_2	6.03	-44.31	45.64
A_3	5.27	-38.60	46.88
A_4	6.03	-8.49	48.47
A_5	5.27	-54.61	45.81
A_6	6.03	-48.36	45.78

8.3.2. Determination of weight coefficient

Detailed calculation process and results to determine weight coefficients is given below:

(1) Standardization of criteria

Standardized matrix Y is constructed by deviation standardization method using the equation (8.4) in the Excel spreadsheet function calculation, as seen Figure 8.2.

B8 =(B3-MIN(B3:G3))/(MAX(B3:G3)-MIN(B3:G3))

Criteria	Alternative					
	Merbau A	Merbau B	Aluminum A	Aluminum B	Polycarbonate A	Polycarbonate B
Energy-saving rate of building envelope (ΦENV) (%)	5.27	6.03	5.27	6.03	5.27	6.03
NPV(LCC)(k £)	-53.01	-44.31	-38.6	-8.49	-54.61	-48.36
LCCO2 (kg CO2/m2/year)	45.75	45.64	46.88	48.47	45.81	45.78
Y	0.000	1.000	0.000	1.000	0.000	1.000
	0.035	0.223	0.347	1.000	0.000	0.136
	0.039	0.000	0.438	1.000	0.060	0.049

Figure 8.2 Screenshot of standardized matrix Y

$$Y = \begin{bmatrix} 0.000 & 1.000 & 0.000 & 1.000 & 0.000 & 1.000 \\ 0.035 & 0.223 & 0.347 & 1.000 & 0.000 & 0.136 \\ 0.039 & 0.000 & 0.438 & 1.000 & 0.060 & 0.049 \end{bmatrix}$$

Since a valid value cannot be calculated through the normalization process when the value of y_{ij} is 0, a non-negative translation is performed on the data in the above matrix Y. The purpose of non-negative translation is to make slight adjustments to the original data to ensure that all processed data are non-negative values and therefore avoiding the situation where data cannot be processed in the subsequent calculations. This method not only ensures the scientific and effectiveness of the data, but also improves the accuracy and reliability of the analysis (CSDN, 2020). In this circumstance, 0.01 is added to the overall data in the standardized matrix Y, which can be seen in the following standardized matrix Y' after non-negative translation:

$$Y' = \begin{bmatrix} 0.010 & 1.010 & 0.010 & 1.010 & 0.010 & 1.010 \\ 0.045 & 0.233 & 0.357 & 1.010 & 0.010 & 0.146 \\ 0.049 & 0.010 & 0.448 & 1.010 & 0.070 & 0.059 \end{bmatrix}$$

The specific gravity matrix P is generated by using the equation (8.5) in the Excel spreadsheet function calculation:

$$P = \begin{bmatrix} 0.003 & 0.330 & 0.003 & 0.330 & 0.003 & 0.330 \\ 0.025 & 0.130 & 0.198 & 0.561 & 0.006 & 0.081 \\ 0.030 & 0.006 & 0.272 & 0.613 & 0.043 & 0.036 \end{bmatrix}$$

(2) Calculation of the criteria weight using the entropy weight method

The entropy values e_1, e_2, e_3 are determined by using the equation (8.6) in the Excel spreadsheet function calculation, which can be constructed in the entropy value matrix E:

$$E = \{0.644, \quad 0.689, \quad 0.582\}$$

The difference coefficient values g_1, g_2, g_3 are determined by equation (8.7), and construct in the difference coefficient matrix G:

$$G = \{0.356, \quad 0.311, \quad 0.418\}$$

The weight coefficient values ω_1, ω_2, ω_3 are determined by equation (8.8), and construct into the weight coefficient matrix W. In this specific case, when considering the application of fixed external shading devices, the criteria with the highest weight coefficient value is 'life cycle carbon emission amount', accounting for 38.5% among the three identified criteria. This follows by the criteria regarding 'energy-saving rate of building envelope', accounting for 32.8%, and 'net present value of the life cycle cost', which accounts for 28.7%. It can be inferred that the criteria of 'life cycle carbon emission amount' and 'energy-saving rate of building envelope' have relatively important impact on the selection of the appropriate fixed external shading design for the studied educational building. It can be further assumed that when scoring the fixed external shading facilities for comprehensive criteria assessment, the values of energy-saving, economic and carbon emission criteria are multiplied by their respective weight coefficient values, namely 32.8%, 28.7% and 38.5%, thus obtain the weighting score of each criteria.

$$W = \{0.328, \quad 0.287, \quad 0.385\}$$

8.3.3. Application of ELECTRE I method

As illustrated in Figure 8.3, the performance values regarding six alternatives on three criteria as well as the respective weight coefficients have been input in the Excel spreadsheet to perform XLSTAT calculation. The first result is a full set of descriptive statistics given per alternative, including respective minimum value, maximum value, mean value and standard deviation values (see Figure 8.4). Figure 8.5 shows the concordance matrix that represents the superiority of concordance between alternatives. Another importance matrix is the discordance matrix shown in Figure 8.6.

	A	B	C	D	E	F	G	H	I
1	Criteria/Alternative	Merbau A	Merbau B	Aluminum A	Aluminum B	Polycarbonate A	Polycarbonate B	Criteria	Weight
2	ΦENV	5.27	6.03	5.27	6.03	5.27	6.03	ΦENV	0.328
3	NPV(LCC)	-53.01	-44.31	-38.6	-8.49	-54.61	-48.36	NPV(LCC)	0.287
4	$LCCO_2$	45.75	45.64	46.88	48.47	45.81	45.78	$LCCO_2$	0.385

Figure 8.3 Data input of performance and weight coefficient regarding six shading alternatives on three criteria

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Merbau A	3	0	3	-53.010	45.750	-0.663	49.647
Merbau B	3	0	3	-44.310	45.640	2.453	45.082
Aluminum A	3	0	3	-38.600	46.880	4.517	42.745
Aluminum B	3	0	3	-8.490	48.470	15.337	29.598
Polycarbonate A	3	0	3	-54.610	45.810	-1.177	50.519
Polycarbonate B	3	0	3	-48.360	45.780	1.150	47.259

Figure 8.4 Descriptive statistics matrix for ELECTRE I

(Source: Calculation results by XLSTAT 2022.)

a/b	Merbau A	Merbau B	Aluminum A	Aluminum B	Polycarbonate A	Polycarbonate B
Merbau A	1.000	0.615	1.000	1.000	0.713	1.000
Merbau B	0.385	1.000	0.672	1.000	0.385	0.713
Aluminum A	0.328	0.328	1.000	1.000	0.328	0.328
Aluminum B	0.000	0.328	0.000	1.000	0.000	0.328
Polycarbonate A	0.615	0.615	1.000	1.000	1.000	0.615
Polycarbonate B	0.000	0.615	0.672	1.000	0.385	1.000

Figure 8.5 Concordance matrix for ELECTRE I

(Source: Calculation results by XLSTAT 2022.)

a/b	Merbau A	Merbau B	Aluminum A	Aluminum B	Polycarbonate A	Polycarbonate B
Merbau A	0.000	0.189	0.312	0.965	0.001	0.101
Merbau B	0.002	0.000	0.124	0.777	0.004	0.003
Aluminum A	0.000	0.016	0.000	0.653	0.000	0.016
Aluminum B	0.000	0.000	0.000	0.000	0.000	0.000
Polycarbonate A	0.035	0.223	0.347	1.000	0.000	0.136
Polycarbonate B	0.000	0.088	0.212	0.864	0.001	0.000

Figure 8.6 Discordance matrix for ELECTRE I

(Source: Calculation results by XLSTAT 2022.)

The outranking results in Figure 8.7 indicate that columns of Aluminum A and Aluminum B contain 1 on row 1 and 5, row 1, 2, 3, 5 and 6, respectively. This means that Aluminum A over ranks Merbau A and Polycarbonate A, Aluminum B over ranks Merbau A, Merbau B, Aluminum A, Polycarbonate A and Polycarbonate B. The 0 value means that there is no over ranking. To ease the interpretation of this matrix, XLSTAT deduces the Ranking table below (see Figure 8.8).

a/b	Merbau A	Merbau B	Aluminum A	Aluminum B	Polycarbonate A	Polycarbonate B
Merbau A	0.000	0.000	1.000	1.000	0.000	1.000
Merbau B	0.000	0.000	0.000	1.000	0.000	0.000
Aluminum A	0.000	0.000	0.000	1.000	0.000	0.000
Aluminum B	0.000	0.000	0.000	0.000	0.000	0.000
Polycarbonate A	0.000	0.000	1.000	1.000	0.000	0.000
Polycarbonate B	0.000	0.000	0.000	1.000	0.000	0.000

Figure 8.7 Outranking matrix for ELECTRE I

(Source: Calculation results by XLSTAT 2022.)

Action	Rank
Aluminum B	1
Aluminum A	2
Polycarbonate B	3
Merbau B	4
Polycarbonate A	5
Merbau A	6

Figure 8.8 Ranking table for ELECTRE I

(Source: Calculation results by XLSTAT 2022.)

Assessment result from the above ranking table indicates that Aluminum B is the optimum external shading options for decision-making in the building design stage, followed by Aluminum A. Polycarbonate B and Merbau B rank the third and fourth place. Polycarbonate A and Merbau A less fit to the whole criteria and rank at the end of the table. Furthermore, it can be inferred from the multi-criteria assessment results applying ELECTRE I that, the material used to make the external shading devices is an important factor that needs to be considered during the building design stage, rather than the size and dimension of the devices. Among the three identified recycling materials on three specific criteria in terms of building energy consumption, economy and environment, Aluminum made device is suggested to be the most preferred choice.

8.4. Discussion and implications

Further discussion will be conducted in conjunction with the feedback of the preliminary interviews. Feedback from the telephone interviews with the respondents stressed the lack of regulatory provisions regarding the assessment of fixed external shading equipment in ASGB-2019, e.g., corresponding scoring methods, evaluation criteria, and weighting system, etc. In view of the above existing problems, this part of research proposes a multi-criteria assessment method (MCDA) for evaluation of the fixed external shading devices, based on the entropy weight and ELECTRE I method. A weighting matrix for the fixed external shading devices has been developed, including three evaluation criteria and corresponding weight coefficients (see Table 8.3).

Table 8.3 Weighting matrix for the fixed external shading devices

Criteria	Weight coefficient
Energy-saving rate of building envelope	32.80%
Net present value of the life cycle cost	28.70%
Life cycle carbon emission amount	38.50%

In terms of data collection, the values regarding 'energy-saving rate of building envelope' can be generated from the BESI simulation. The 'net present values of life cycle cost' with respect to the external shading devices are estimated based on the market price of the recyclable material, and the values of 'life cycle carbon emission' of the whole building are obtained from the CEEB simulation. The above data sources are objective. In terms of the weighting system, assuming that the assessment score for the fixed external shading devices is added to the current standard (ASGB-2019). For example, 5 points, the scores of the identified criteria are 1.64, 1.435, and 1.925 respectively. Furthermore, it is worth mentioning that the weight coefficients of this research are calculated based on the previous research results regarding the three specific criteria. The values of the weight coefficient may change with the number of evaluation criteria and the corresponding performance values regarding each shading alternative. This objective weight calculation method can be applied in the quantitative research process, including but not limited to the research area of building materials, building components, etc. Moreover, the XLSTAT 2022 plug-in in the EXCEL spreadsheet is used for automatically computation regarding ELECTRE I, and the ranking table for the evaluation alternatives can be generated through one-click operation. Although the final assessment result may change with the collected data values, this assessment method is easy to operate and can be applied to various research fields.

8.5. Summary

This part of the research presents the methodology and the application of MCDA method to assess the appropriate fixed external shading design for a green educational building project, which are located in the hot summer and warm winter climate region of China. This study contributes to propose a multi-criteria assessment method to analyze and compare the shading alternatives. An optimum and sustainable external shading solution for the studied building has been delivered. The entropy weight method and ELECTRE I method are applied for computation to obtain the final ranking table. In addition, this research aims to clarify whether these findings can be generalized to the real assessment conditions. The criteria adopted in these two methods of this study are classified as the ‘energy-saving rate of building envelope’, ‘net present value of life cycle cost’, and the ‘life cycle carbon emission of the building’. The decision matrix A regarding six shading alternatives with respect to three specific criteria is constructed for subsequent computation to determine the weight coefficients and the final ranking table.

The reason why this research adopts the entropy weight method and ELECTRE I by using the XLSTAT 2022 plug-in method lies in these methods have objective, solid and appropriate mathematical background and perform a holistic study. Hence, this research contributes to:

(1) A choice of comparing the proposed external shading alternatives integrating two quantitative analysis techniques that promote the desired results of the study.
(2) A choice of demonstrating a methodology that avoids judgement confusion.
(3) A method of applying quantitative criteria affecting the options of external shading configuration.
(4) A suggestion of a weighting matrix based on the real green building case for assess the fixed external shading devices, including the identified criteria and weight coefficients.
(5) The first research by combining the entropy weight method and ELECTRE I by using the XLSTAT plug-in in the research area of green building assessment, assessment of sustainable building components and materials, assessment of external shading facilities.

According to entropy weight method, the criteria with relatively important impact on the fixed external shading devices are determined, e.g., the ‘life cycle carbon emission amount’ and the ‘energy-saving rate of building envelope’, respectively accounting for 38.5% and 32.8% among the three identified criteria. This is followed by the criteria regarding the ‘net present value of the life cycle cost’, accounting for 28.7%. By using the entropy weight method and ELECTRE I, the optimum shading solution is chosen as Aluminum B among the six solutions, which have the highest-ranking values of 1. The ranking order concludes as Aluminum B ranked the first place. Aluminum A ranked the second place. Polycarbonate B and Merbau B ranked the third and fourth place. Polycarbonate A and Merbau A ranked at the end of them. All in all, assessment results indicate that the aluminum shading material is suggested to be the most preferred choice when considering fixed external shading design for green building within this hot-humid climate area.

Chapter 9. Conclusions and Recommendations

To conclude the thesis, this chapter provides a summary of research findings and examines to what extent all the objectives of this study have been achieved. The contribution of this research to the existing relevant literature, as well as the recommendations for the Chinese green building evaluation standards regarding the comprehensive criteria assessment method for the fixed external shading design are presented. Finally, this chapter further discusses the limitations of this study and suggestions for future research work.

9.1. Summary of research findings

Chinese government, and construction industry began to carry out assessment for green building projects since the announcement of ESGB-2006 in 2006. ASGB-2019 is the current implementation evaluation standard. An effective green building evaluation standard system can help to improve the energy-saving and carbon emission reduction effects of buildings, increase the comfort of indoors and outdoors environment, and enable the construction industry to move towards energy efficiency, economically and environmentally sustainable development. However, it has been observed that various problems have occurred in the assessment practice under the implementation of ASGB-2019. In particular, the fixed external shading design, one of the widely used passive building measures in China, of which overall values to the building have been overlooked. Meanwhile, there is currently a lack of regulatory provision for the comprehensive assessment of the fixed external shading devices in ASGB-2019. Further, it is difficult for people to know the overall benefits of using fixed external shading devices to the building, such as their energy-saving and carbon emission impact on the building, as well as the initial investment required for using shading devices.

Considering the improvement of the comprehensive assessment method of fixed external shading design in ASGB-2019, this research has investigated critically the impact of fixed external shading devices on a green educational building in hot summer and warm winter climate region in terms of energy-saving, economic and environmental perspective. An optimum shading case (Integrated shading I) with the highest energy-saving effect has been determined among 21 selected fixed external shading design, which energy-saving rate of building envelop (Φ_{ENV}) is 6.03%. As for the economic impact, Polycarbonate A is the case with the highest initial investment amongst the six shading alternatives, which NPV of LCC is

£54,607.87. This is an overall consideration of the base and optimal energy-saving shading alternatives, as well as three specific recyclable materials, e.g., merbau, aluminum, and polycarbonate. The environmental simulation results demonstrate the $LCCO_2$ emission amounts among the six shading options in 50-year lifespan from high to low, namely Aluminum B (5,182.12 tCO_2), Aluminum A (5,011.61 tCO_2), Polycarbonate A (4,897.14 tCO_2), Polycarbonate B (4,893.99 tCO_2), Merbau A (4,891.44 tCO_2), and Merbau B (4,879.61 tCO_2). The comprehensive MCDA method delivers a weighting matrix for the assessment of fixed external shading devices, including three specific criteria, e.g., 'energy-saving rate of building envelope', 'net present value of the life cycle cost' and 'life cycle carbon emission amount', whose weight coefficient are 32.8%, 28.7% and 38.5% respectively. Aluminum B is proposed to be the optimum shading solution through automatic ranking by using ELECTRE I method. This proposed comprehensive evaluation method can be used as a reference for improvement direction of assessment method regarding the fixed external shading devices in green building industry in the future. To achieve the overall aim of the research, the conclusions for five objectives are given below.

(1) Objective 1:

The first objective of this research was to investigate the development and actual implementation problem of external shading-related provisions in three versions of Chinese green building evaluation standards. A review of relevant literature and policy documents is required for the exploration of green building-related policies and evaluation standards. A series of comparative studies have been conducted on the general contents, as well as the specific provisions and scoring requirements related to building external shading among ESGB-2006, ASGB-2014 and ASGB-2019. The policy application scope, evaluation timeline, evaluation objects, evaluation content, rating method, certification levels, and the development from ESGB-2006 to ASGB-2019 have been clarified. This supported that there was an issue in the assessment of external shading during the green building evaluation process. It was found that the current assessment provisions relevant to building shading in ASGB-2019 focused on the adjustable shading facilities rather than the fixed external shading design. In addition, it can be noted that there is a lack of qualitative or quantitative regulations on the energy-saving and shading effects of fixed external shading designs in ASGB-2019 (e.g., assessment methods, weighting systems, and rating levels, etc.). Further analysis from the investigation regarding the existing problems revealed that the external shading measures are not separately assessed in the pre-evaluation stage in green building evaluation practice. This is largely due to the lack of an effective method for the assessment of fixed external shading devices, which lays the foundation of the subsequent study regarding the investigation of their impact on green building assessment and the suggestion of a comprehensive assessment method.

(2) Objective 2:

The second objective of this research was to assess the energy-saving impact of various fixed external shading designs on a green educational building in Shenzhen. It was found from the investigation that the criteria value regarding the energy-saving rate of building envelope is practically preferred to be used to assess the energy-saving impact of various fixed external shading alternatives on building by using BESI 2024 building energy efficiency simulation software. Further simulation analysis indicated that the energy-saving rate of building envelope is proportional to the protruding length of the shading devices and the length of the baffle. In addition, there will be an increase of 0.062% in energy-saving rate of building envelope for every 100mm increase in horizontal protrusion length, and an increase of 0.11% in energy-saving rate of building envelope for every 100mm increase in vertical protrusion length. Finally, the optimum fixed external shading design with the best energy-saving effect among the 21 proposed shading cases, which is Integrated shading I, has been generated through the conduction of building simulation and comparative analysis. With 1000mm protrusion length of horizontal shading board and 600mm of vertical shading board, the annual heating and cooling energy consumption of Integrated shading I is 486,909kWh, and the value of energy-saving rate of building envelope is 6.03%. This result is to be used for subsequent comprehensive assessments.

(3) Objective 3:

The third objective of this research was to assess the initial investment of the fixed external shading devices on the studied green educational building by LCCA. Document survey with the local external shading product manufacturers, building material suppliers, and renewable resource recycling companies assist in providing information on the cost data collection of the external shading components during the construction, installation, O&M, and disposal stages. The current discount rate of 5.04% announced by the Bank of China is applied to estimate the PV of the costs during the O&M and disposal stages. CEEB 2024, a local carbon emission simulation software, helps to estimate the annual power consumption of different external shading designs, thus calculate the respective annual electricity expenditure savings by adopting fixed external shading devices. Regarding the respective initial investments, the NPV of LCC regarding the six external shading cases can be obtained by summing up the PV of costs at the four life cycle stages in 50 years lifespan. From LCCA, it has been concluded that the external shading cases with initial investment from high to low are Polycarbonate A (£54,607.87), Merbau A (£53,013.14), Polycarbonate B (£48,358.82), Merbau B (£44,310.69), Aluminum A (£38,601.86), and Aluminum B (£8,491.10).

(4) Objective 4:

The fourth objective of this research was to carry out $LCCO_2A$ of the fixed external shading devices on the studied educational building by using CEEB 2024. This is to assess their environmental impact on building in 50-year lifespan. The carbon emission amounts regarding the four stages of the building, namely building materials production and transportation, building construction, building operation, and building demolition, have been estimated through software simulation. The $LCCO_2$ emission amounts regarding six fixed external shading devices have been further calculated. The optimum external shading design with the lowest $LCCO_2$ emission amount is generated through comparative analysis. From $LCCO_2A$, it has been concluded that the external shading options with $LCCO_2$ amounts from high to low are Aluminum B (5,182.12 tCO_2), Aluminum A (5,011.61 tCO_2), Polycarbonate A (4,897.14 tCO_2), Polycarbonate B (4,893.99 tCO_2), Merbau A (4,891.44 tCO_2), and Merbau B (4,879.61 tCO_2).

(5) Objective 5:

The fifth objective of this research was to conduct MCDA of six fixed external shading devices on three specific assessed criteria for the studied green educational building by using ELECTRE I method. With the help of the entropy weight method and a XLSTAT plug-in in Excel, the ELECTRE I method has been achieved. The weight coefficients regarding the specific three criteria have been determined and a final ranking table has been automatically generated. The values of weight coefficients reflect the importance of the assessed criteria in this specific assessment, which is 32.8% for 'energy-saving rate of building envelope', 28.7% for 'NPV of LCC', and 38.5% of '$LCCO_2$ amount'. The generated weighting matrix is expected to provide a quantitative improvement direction for the assessment of the fixed external shading devices in ASGB-2019. It can be concluded from the analysis that Aluminum made device

(Aluminum B) is the most preferred choice among the three assessed shading materials (totally six shading options). The preferred external shading choice is the first-ranked alternative in the ranking table, which can provide the structural engineers with the suggested external shading solution at the green building design stage. Further, integrating the multi-criteria decision assessment into the early design stage of a specific green building project, can better reflect the impact of fixed external shading strategies on energy conservation, economy, and environment during the assessment process.

9.2. Contributions and recommendations

The novelty of this research lies in the proposal of a MCDA method based on ELECTRE I technique for comprehensive evaluation of the fixed external shading devices for green building assessment. The best ranked fixed external shading solution amongst the shading alternatives can be automatically generated. Contributions to this research area are given below.

(1) This research demonstrates the specific process of green building assessment in China based on a real green building assessment case.
(2) This research explores the problems existing in the assessment of fixed external shading devices in the green building assessment practice within hot summer and warm winter climate region.
(3) This research demonstrates a building energy efficiency simulation process based on a real green education building assessment case by BESI 2024 in the early design stage. The analysis process of energy-saving impact regarding various types of shading options has been illustrated.
(4) This research produces an analysis framework applying LCC method, for estimating the NPV of costs at each life cycle stage regarding the fixed external shading components.
(5) This research establishes a $LCCO_2$ calculation model to represent the analysis of carbon emission amount at each building life cycle stage with respect to the proposed external shading alternatives by using CEEB 2024.
(6) This research provides an automatic calculation method for multi-criteria decision-making based on ELECTRE I by using the XLSTAT 2022 plug-in in Excel, to inform the structural engineers and evaluation experts in green building design and assessment practice.

(7) This research develops a weighting matrix for the fixed external shading devices, including three categories of criteria and corresponding weighting coefficients, to provide the policy makers involved in green building assessment with an improvement direction for the assessment of fixed external shading devices in ASGB-2019.
(8) This research demonstrates that aluminum is the priority for making external shading devices among the three studied recyclable materials, considering the energy-saving impact, life cycle cost and carbon emissions of the material. A better choice of materials for shading equipment production is provided for the shading product manufacturers.

It has been recognized that green building assessment has a significant impact on the sustainable development of buildings, both positively and negatively. Stakeholders in green building design and assessment, such as green building assessment experts, professors in the field of green building research, local architectural design institute officials, relevant policy standard makers, energy-saving building structural engineers, etc., have played a significant role in promoting the development of green building assessment policies and practices, which has become a driving force for innovation in sustainability research. One of findings from the research areas is to propose a multi-criteria assessment method to assist the professional designers and evaluation experts for optimizing shading design decisions. It is critical to assist the professionals in making more informed decisions when the time to influence changes.

9.3. Limitations and future work

This research project fills in the gap of previous study to propose a mixed methodology for multi-criteria assessment of fixed external shading devices, integrating quantitative and qualitative research approaches. However, some research gap and limitations still exist in the current methods, vary from the software, case study, external shading design strategies, to the studied climate region, etc. Limitations of this study lies in:

(1) The building simulation software used in this research are developed in China, and language problems exist in the Chinese version of the operating interface when promotion in the global market in the future.
(2) The building case used for this research is a small public building, and fewer influencing factors need to be considered in the simulation process compared with other type of buildings.

(3) The protrusion length of the fixed external shading boards regarding all the windows are set to the same size, without considering the optimal protrusion length of the shading panels in different building orientations.
(4) The studied climate region is the hot summer and warm winter area in China, where heat preservation in winter generally does not need to be considered. There are fewer influencing factors to be considered in the building energy-saving simulation compared to other climate areas.

In order to make this study more universal and closer to the assessment practice, future research will embrace the application of more sophisticated methods to explore the comprehensive evaluation of external shading facilities. The consideration factors of future research will be further extended as follow:

(1) Consider other types of external shading facilities, including various forms of fixed or adjustable external shading measures, as well as the optimal design of the protrusion length regarding the external shading devices in different orientations.
(2) Consider different type of recyclable materials.
(3) Consider more thermal assessment criteria (e.g., lighting effect, ventilation effect, thermal comfort effect, etc), as well as key social criteria, (e.g., aesthetics) and economic criteria (e.g., Internal Rate of Return (IRR), Benefit/Cost Ratio, Payback Period, etc).
(4) Consider using other types of MCDA methods.
(5) Consider more advanced building energy efficiency simulation software, such as Energyplus. DesignBuilder, etc.
(6) Consider other building types, such as large public buildings, residential buildings, hospital buildings, university buildings, etc.
(7) Consider other climate regions where heat preservation in winter and heating insulation in summer are both required.

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Appendices

Appendix A. Service process of green building evaluation for the investigated green building consulting company

Development process of green building project (construction project parties)		**Evaluation process of green building (green building consulting company)**	**The specific working content of green building evaluation**
/	/	Pre-project preparation	1. Familiar with project information. 2. Understand the local green building policy requirements and construction project parties' positioning needs for the project. 3. Familiar with the location environment of the project.
Investment and decision-making stage	Preparation of project proposals	Preparation of the project approval part of the "Green Building Monograph"	Provide "Green Building Monograph"
	Conduct building energy efficiency	Conduct building energy efficiency	1. Government investment projects: energy-saving review opinions need to be obtained before applying for scientific research. 2. Enterprise investment projects: energy conservation review opinions need to be obtained before starting construction.
	Conduct a feasibility study of the project	Preparation of the planning part of the "Green Building Monograph"	Provide "Green Building Monograph"
	Conduct project evaluations	/	/
	Conduct project decision	/	Obtain project approval
	Conduct land use planning	/	/
Engineering design stage	Conduct schematic design	Provide physical environment analysis and recommendations	1.In the early stage of the project, a detailed analysis of the microclimate of the site will be conducted combined with the site layout, based on the local climate and ecological environment. (e.g., site acoustic environment optimization, ventilation analysis, site thermal humidity, solar radiation, sunlight, etc.). 2. Specific suggestions will be given based on the analysis results.

		Conduct green building self-evaluation V1.0	Analyse the project's feasibility of meeting green building standards, put forward difficulties and highlights, communicate and report with construction project parties and designers, provide guidance for the next design step.
		Estimate project increment	Estimate the green building increment of the project, combining with a series of documents such as "Green Building Economic Indicators", and delivery it to the construction project parties.
		Prepare the technical design plan of the project	Report the key and difficult technologies based on the needs and characteristics of the project, such as: 1. Selection of combined wall glass for high-star residential buildings. 2. The impact of building HVAC load reduction on energy conservation. 3. Analysis on green technology application of similar competing products in the same regional market.
			Conduct special reports on possible highlight technologies of the project, such as: 1. Feasibility of near-zero carbon park construction 2. Optimized design of indoor units 3. Passive design 4. Nearly zero energy consumption 5. Near-zero carbon buildings 6. Tranquil House
		Provide a programme verification opinion	/
	Conduct preliminary design and approval of the project	Conduct green building self-evaluation V2.0	Conduct a second round of special reports based on the preliminary design documents of the project, organize the documents including provided information and material according to the opinions of different parties, to guide the deepening of the drawing design.
		Prepare documents including provided information and material related to green building	Examine the preliminary design documents of the project, issue a proposal of "Green building related documents of provided information and material based on green building requirements to guide the preliminary design.
		Prepare other special cooperation documents	In the preliminary design stage, relevant reporting documents are issued for the project according to policy requirements. For example, special low-carbon design is required for government investment projects in Nanshan District, special monograph is provided in the initial design stage, including the project increment in the budget document.
		Estimate budget	Some special designs, such as low-carbon design increments, need to be calculated in the budget estimate.
		Examine architectural drawings	Examine the architectural drawings of various majors, issue examination opinions to guide the designers to adjust the drawings according to green building requirements.
		Conduct the application of project planning permits	Cooperate with the project to submit plans and regulations, provide a "Green Building Monograph" that meets the requirements, and assist construction project parties to obtain the project planning permit.
	Construction drawing	Examine architectural drawings	Examine the professional construction drawings provided by the designer and issue guidance documents.

	design and approval	Conduct green building self-evaluation V3.0	Conduct the third round of special reports based on the preliminary design documents of the project and organize the documents of provided information and material according to the opinions of different parties, to guide the in-depth design of the construction drawings.
		Conduct energy-efficient design	Complete the energy-saving design of the project according to energy-saving standards and pass the examination.
		Conduct energy-efficient optimization	Evaluate the energy-saving design of the project and examine whether the project material selection can be optimized to reduce energy-saving costs based on meeting the standard requirements for energy conservation and green building.
		Preparation of construction drawing design documents	Design drawings according to the project construction drawing, construction drawing examination documents are issued in accordance with green building requirements and submitted to a third-party evaluation agency for evaluation.
		Modification documents including provided information and material related to green building	According to the construction drawing examination opinions issued by a third party, documents of provided information and material will be given to each cooperating parties for document adjustment.
		Completion of construction drawing examination (compulsory examination)	Respond to construction drawing examination comments and cooperate with the project parties to obtain the construction drawing examination certificate.
		Completion of accurate examination	A third-party organization will be hired to conduct examination and issue opinions. Green building will cooperate to modify the construction drawings. Green building project will pass the pre-evaluation after re-examination.
Procurement and construction stage	Preparation for construction	Conduct a special examination	Examine special design documents such as landscape, curtain wall, decoration, etc., and issue examination opinions to ensure that the construction drawings satisfy green building requirements.
		Conduct construction tenders	In the early stage of project bidding, according to the green building requirements, "Green Building Construction Bidding Document" will be issued to make binding requirements for material procurement.
		Construction disclosure	In the early stage of construction, green building construction briefing training is provided to the project construction parties and general contractors, reminding them to summarize green building materials during the project construction and procurement process.
		Feedback on the construction process	Construction parties, supervisors, etc., collect materials according to green building requirements during the construction process and provide regular feedback.
		Spot checks on green buildings	During the construction process, the housing construction departments in each district will organize spot checks of green buildings from time to time to check the construction status of the project site and the implementation of green buildings. Green building consulting company will cooperate with construction project parties and the competent authorities to conduct spot checks to ensure the smooth progress of the project.
		Green building inspection	Various project performance will be monitored before project acceptance and pre-evaluation, such as indoor background noise, indoor pollutant concentration, indoor light environment, etc.

		Pre-evaluation of green buildings	A pre-evaluation application for the project will be conducted before the completion and acceptance of the project. Construction project parties will organize the information and submit application appeals, participate in the pre-evaluation meeting, answer questions on site, pass expert examination, and obtain a green building pre-evaluation report.
	Construction permits	/	/
	Construction and Installation	/	/
	Preparation for production	/	/
		Green marketing	1. Green marketing document production 2. Green operation team training 3. Media promotion and marketing cooperation 4. Green building content display in the house sales office 5. Promotion of green aspects in the house sales office
Construction delivery stage	Completion acceptance	Green building conformity evaluation	Before the special acceptance of the green building project, cooperate with a qualified third-party evaluation agency and construction project parties to participate in the green building compliance assessment, evaluate the project's on-site compliance status, provide on-site acceptance technical support services, and cooperate with construction project parties to pass the compliance evaluation.
		Special acceptance of green buildings	Led by the construction unit and jointly carried out by various institutions e.g., design, construction, supervision, etc.
		Before delivery	1. Cooperate with the preparation of project sales contracts and specify relevant green building information in the contracts. 2. Cooperate with construction project parties to prepare a green building instruction manual before delivery to clarify the content of green building.
	Completion settlement and final accounts	/	/
	Post-evaluation of the project	Green building label declaration	After completion: 1. Organize materials after project completion and acceptance. 2. Submit a declaration request to the competent authority. 3. Participate in the project examination meeting and answer questions on-site, pass the green building label examination, and obtain the signboard.
			Operational stage: 1. Propose green building precautions during the operation process and issue plans for guidance. 2. Organize data and some materials during the operation process, 3. Submit a declaration request to the competent authority,

			4. Participate in the project examination meeting and answer questions on-site, pass the green building label review, and obtain the signboard.
		Application for green building demonstration projects and innovation awards	After obtaining the green building label, it submits a green building demonstration project subsidy application to the municipal housing and construction department and cooperates with the examination department to conduct "formal examination, expert examination, project verification," etc. to ensure that the project passes the examination and obtains municipal financial subsidies.
		Special consultation on green operation management services	/

(Source: the investigated green building consulting company in Shenzhen)

Appendix B. The simplified version of the green building self-evaluation report for a one-star kindergarten project in Shenzhen

4 Safety and Durability					
Attribute item	**Indicator item**	**Provision's code**	**Provision content**	**Full score**	**Results (satisfied/score)**
Prerequisite items	/	4.1.1	Geologically dangerous areas such as landslides and mudslides should be avoided on the site. Flood-prone areas should be equipped with reliable flood control infrastructure. There should be no threat from hazardous chemicals, flammable, and explosive sources, as well as harm of electromagnetic radiation and radon-containing soil.	/	Satisfied
		4.1.2	The building structure should meet the requirements of bearing capacity and building use functions. Building envelopes such as external walls, roofs, doors, windows, curtain walls and external insulation should meet the requirements of safety, durability, and protection.	/	Satisfied
		4.1.3	External facilities such as external shading, solar energy facilities, air-conditioning outdoor units, and external wall flower ponds are to be designed and constructed in a unified manner with the main structure of the building, and to meet the conditions for installation, inspection, and maintenance.	/	Satisfied
		4.1.4	Non-structural components, equipment and subsidiary facilities inside the building should be firmly connected and adapt to the deformation of the main structure.	/	Satisfied
		4.1.5	The external doors and windows of the building must be firmly installed, and their wind pressure resistance and watertight performance should comply with the relevant national standards.	/	Satisfied
		4.1.6	The floors of toilets and bathrooms should be provided with waterproof layers. The walls and ceilings should be provided with moisture-proof layers.	/	Satisfied
		4.1.7	Passage spaces such as corridors and evacuation passages should be kept clear and meet the requirements for emergency evacuation and emergency rescue.	/	Satisfied
		4.1.8	Warning and guidance sign system should be equipped for safety protection.	/	Satisfied
Scoring items	Safety	4.2.1	Adopt performance-based seismic design and reasonably improve the seismic performance of the building, with a score of 10 points.	10	0
		4.2.2	Take protective measures to ensure personnel safety, with a total score of 15 points: 1. Take measures to improve the safety protection level of balconies, external windows, protective railings, etc., 5 points are awarded. 2. All entrances and exits of the building are equipped with protective measures to prevent accidental falling from external wall coverings, door and window glass, combining with shading, windshield or rain protection measures in areas where people pass, 5 points are awarded. 3. Use the site or landscape to form a buffer zone or isolation zone that can reduce the risk of falling objects. 5 points are awarded.	15	15
		4.2.3	Adopt products or accessories with safety protection functions, with a total score of 10 points. The scores are awarded separately and accumulated according to the following rules: 1. Use glass with safety protection function, 5 points are awarded.	10	10

			2. Use doors and windows with anti-pinch function, 5 points are awarded.		
		4.2.4	Anti-skid measures are set up on indoor and outdoor floors or pavements, with a total score of 10 points. The scores are awarded separately and accumulated according to the following rules: 1. Anti-skid measures should be installed at building entrances and platforms, public corridors, elevator lobbies, kitchens, bathrooms, toilets, etc. The anti-skid level should not be lower than the Bd and BW levels, which specified in the current industry standard "Technical Specifications for Anti-Slip Engineering of Building Ground Engineering" JGJ/T 331. 3 points are awarded. 2. The indoor and outdoor activity areas of the building adopt anti-skid floors. The anti-skid level reaches the Ad and AW levels, which specified in the current industry standard "Technical Specifications for Anti-Slip Engineering of Building Ground Engineering" JGJ/T 331. 4 points are awarded. 3. The anti-slip level of building ramps and stair treads shall meet the Ad and AW levels stipulated in the current industry standard "Technical Specifications for Anti-Slip in Building Floor Engineering" JGJ/T 331 or be increased by one level according to the level of the horizontal ground, and anti-skid structural technical measures such as anti-skid strips shall be adopted. 3 points are awarded.	10	10
		4.2.5	Measures are taken to divert pedestrians and vehicles, and the pedestrian and bicycle traffic systems have sufficient lighting, with a score of 8 points.	8	8
	Durability	4.2.6	Adopt measures to improve the adaptability of the building, with a total score of 18 points, which will be scored separately and accumulated according to the following rules: 1. Adopting a universal, open, flexible, and variable use space design, or taking measures to change the building's use functions. 7 points are awarded. 2. The building structure is separated from the construction equipment pipelines. 7 points are awarded. 3. Adopt equipment and facility layout or control methods that are suitable for building functions and space changes. 4 points are awarded.	18	0
		4.2.7	Adopt measures to improve the durability of building components, with a total score of 10 points, which will be scored separately and accumulated according to the following rules: 1. Use pipes, pipelines, and fittings with good corrosion resistance, anti-aging, and durability. 5 points are awarded. 2. Select long-life products for movable parts and consider the same lifespan of the parts combination. When combining parts with different lifespans, adopt a structure that is easy to replace, update and upgrade respectively. 5 points are awarded.	10	10

		4.2.8	Improve the durability of building structural materials, with a total score of 10 points, and the scores are awarded according to the following rules: 1. Building structural materials are designed for durability for 100 years. 10 points are awarded. 2. Use building structural materials with good durability and meet one of the following conditions. 10 points are awarded. 1) For concrete components, increase the thickness of the protective layer of steel bars or use high-durability concrete. 2) For steel components, use weather-resistant structural steel and weather-resistant anti-corrosion coatings. 3) For wooden components, use anti-corrosion wood, durable wood, or durable wood products.	10	0

		4.2.9	Reasonable use of decoration and building materials with good durability and easy maintenance, with a total score of 9 points. The scores are awarded separately and accumulated according to the following rules: 1. Use external facing materials with good durability. 3 points are awarded. 2 Use waterproof and sealing materials with good durability. 3 points are awarded. 3. Use interior decoration materials with good durability and easy maintenance. 3 points are awarded.	9	9
Total score				100	**62**
5 Health and Comfort					
Prerequisite items	/	5.1.1	The concentration of pollutants in indoor air such as ammonia, formaldehyde, benzene, total volatile organic compounds, radon, etc., should comply with the relevant provisions of "Indoor Air Quality Standard" GB/T 18883. Smoking should be prohibited inside and at the main entrance and exit of the building. Signs of no-smoking should be placed in prominent locations.	/	Satisfied
		5.1.2	Measures should be taken to prevent air and pollutants in various places such as kitchens, restaurants, printing and copy rooms, bathrooms, underground garages from colluding into other spaces. Exhaust gas backflow from kitchens and bathrooms should be prevented.	/	Satisfied
		5.1.3	The setting of water supply and drainage systems should meet health requirements and comply with the following regulations: 1. The quality of drinking water should meet the requirements of the current national standard "Hygienic Standard for Drinking Water" GB 5749. 2. Regular cleaning and disinfection plans for water storage facilities such as pools and water tanks should be formulated and implemented. Drinking water storage facilities should be cleaned and disinfected no less than once every six months. 3. Toilets with built-in water seals should be used, and the water seal depth should not be less than 50mm. 4. Non-traditional water source pipelines and equipment should be set up with clear and permanent signs.	/	Satisfied
		5.1.4	The indoor noise level and sound insulation performance of the main functional rooms should comply with the following regulations: 1. The indoor noise level should comply with the minimum requirements in the current national standard "Code for Design of Sound Insulation for Civil Buildings" GB 50118. 2. The sound insulation performance of external walls, partition walls, floors, doors, and windows should meet the minimum requirements in the current national standard "Code for Design of Sound Insulation for Civil Buildings" GB 50118.	/	Satisfied
		5.1.5	Architectural lighting should comply with the following regulations: 1. The quantity and quality of architectural lighting should comply with the current national standard "Architectural Lighting Design Standard" GB 50034. 2. Places where people stay for a long time should use non-hazardous lighting products that comply with the current national standard "Photobiological Safety of Lamps and Lamp Systems" GB/T 20145.	/	Satisfied

			3. The fluctuation depth of the light output waveform of the selected LED lighting products should meet the provisions of the current national standard "Technical Requirements for LED Indoor Lighting Applications" GB/T 31831.		
		5.1.6	Measures should be taken to protect the indoor thermal environment. For buildings that use centralized air-conditioning and heating systems, the design parameters such as indoor temperature, humidity, and fresh air volume should comply with the relevant provisions of the national standard "Code for Design of Heating, Ventilation and Air Conditioning for Civil Buildings" GB 50736. For buildings that use non-central heating and air-conditioning systems, measures or reservations should be put in place to protect the indoor thermal environment.	/	Satisfied
		5.1.7	The thermal performance of the building envelope should meet the following requirements: 1.Under the indoor design temperature and humidity conditions, no condensation may form on the inner surface of the non-transparent building envelope. 2.Condensation should not occur inside the roof and external walls of heating buildings. 3.The thermal insulation performance of the roof and external walls should meet the requirements of the current national standard "Code for Thermal Design of Civil Buildings" GB50176.	/	Satisfied
		5.1.8	The main functional rooms should have on-site independently controlled thermal environment conditioning devices.	/	Satisfied
		5.1.9	Underground garages should be equipped with carbon monoxide concentration monitoring devices linked to exhaust equipment.	/	Satisfied
Scoring items	Indoor air quality	5.2.1	Control the concentration of major indoor air pollutants, with a total score of 12 points. The scores are awarded separately and accumulated according to the following rules: 1.If the pollutants concentration of ammonia, formaldehyde, benzene, total volatile organic compounds, radon, etc., is less than 10% of the limit specified in the current national standard "Indoor Air Quality Standard" GB/T 18883, 3 points are awarded. If it is less than 20%, 6 points are awarded. 2. The annual average indoor PM2.5 concentration is not higher than 25μg/m^3, and the annual average indoor PM10 concentration is not higher than 50μg/m^3, 6 points are awarded.	12	6
		5.2.2	The used decoration materials meet the requirements for hazardous substance limits in the current national green product evaluation standards, with a total score of 8 points based on the following rules: 1.If three or more decoration materials meet the requirements, 5 points are awarded. 2. If five or more decoration materials meet the requirements, 8 points are awarded.	8	5
	Water quality	5.2.3	The water quality of direct drinking water, centralized domestic hot water, swimming pool water, heating and air-conditioning system water, landscape water bodies, etc. meets the requirements of the current relevant national standards, with a score of 8 points.	8	8
		5.2.4	Take water storage facilities related measures such as drinking water pools and water tanks to meet hygiene requirements, with a total score of 9 points. The scores are awarded separately and accumulated according to the following rules:	9	9

			1. Adopt finished water tanks that meet the current national standards, 4 points are awarded. 2. Take measures to ensure that stored water does not deteriorate. 5 points are awarded.		
		5.2.5	All water supply and drainage pipes, equipment, and facilities should be clearly and permanently marked, with a score of 8 points.	8	8
	Sound environment and light environment	5.2.6	Take measures to optimize the indoor acoustic environment of the main functional rooms, with a total score of 8 points. The scores are awarded according to the following rules: 1. If the noise level reaches the average of the lower standard limit and the higher standard limit in the current national standard "Code for Design of Sound Insulation for Civil Buildings" GB50118, 4 points are awarded. 2. If the noise level reaches the high-requirement standard limit in the current national standard "Code for Design of Sound Insulation for Civil Buildings" GB50118, 8 points are awarded.	8	8
		5.2.7	The sound insulation of the main functional room has a good performance, with a total score of 10 points. The scores are awarded separately and accumulated according to the following rules: 1. The airborne sound insulation performance between components and adjacent rooms 1）reaches the average of the low standard limit and the high standard limit in the current national standard "Code for Design of Sound Insulation for Civil Buildings" GB 50118, 3 points are awarded. 2）reaches highly demanding standard limits, 5 points are awarded. 2. If the impact sound insulation performance of the floor plate reaches the average of the low standard limit and the high standard limit in the current national standard "Code for Design of Sound Insulation for Civil Buildings" GB 50118, 3 points are awarded. If it reaches the high standard limit, 5 points are awarded.	10	5
		5.2.8	Making full use of natural light, with a total score of 12 points. The scores are awarded separately and accumulated according to the following rules: 1. At least 60% of the area of the main indoor functional space of a residential building has a lighting illumination value of not less than 300lx. The average number of hours is not less than 8h/d. 9 points are awarded. 2. Public buildings are awarded separately and accumulated according to the following rules: 1) The proportion of the area where the inner area's lighting coefficient meets the lighting requirements reaches 60%. 3 points are awarded. 2) If the average lighting coefficient of the underground space is not less than 0.5% and the ratio of the area of the first floor of the basement reaches more than 10%, 3 points are awarded. 3) The lighting illumination value of at least 60% of the area of the main indoor functional space is not less than the number of hours required for lighting, the average is not less than 4h/d. 3 points are awarded. 3. The main functional room has glare control measures. 3 points are awarded.	12	3
		5.2.9	It has a good indoor heat and humidity environment, with a total score of 8 points. The scores are awarded according to the following rules:	8	0

	Indoor hot and humid environment		1. For buildings that adopt natural ventilation or composite ventilation, if the indoor thermal environment parameters of the main functional rooms of the building are in the adaptive thermal comfort zone for 30% of the time, 2 points are awarded. For each additional 10%, 1 point is awarded, up to the highest score of 8 points. 2. For buildings using artificial cold and heat sources, the main functional rooms must meet the area ratio of Level II of the overall hot and humid environment evaluation of indoor artificial cold and heat sources specified in the current national standard "Evaluation Standard for Indoor Thermal and Moisture Environment for Civil Buildings" GB/T 50785, reaching 60%, 5 points are awarded. For additional 10%, 1 point is awarded, up to the highest score of 8 points.		
		5.2.10	Reasonably optimize the space and floor layout, improve the natural ventilation effect. With a total score of 8 points, and the score is based on the following rules: 1. Residential buildings: The ratio of ventilation opening area to room floor area reaches 12% in hot summer and warm winter areas, or 8% in hot summer and cold winter areas, or 5% in other areas. 5 points are awarded. For additional 2%, 1 point is awarded, up to the highest score of 8 points. 2. Public buildings: 70% of the main functional rooms under typical working conditions in the transition season have an average natural ventilation rate of no less than 2 times/h, 5 points are awarded. For each additional 10%, 1 point is awarded, up to the highest score of 8 points.	8	0
		5.2.11	Set up adjustable shading facilities to effectively improve indoor thermal comfort, with a total score of 9 points. According to the proportion Sz of the area of the adjustable shading facilities to the transparent part of the external window, the score is based on the rules in Table 5.2.11.	9	0
Total score				100	**52**
6 Occupant Convenience					
Prerequisite items	/	6.1.1	A coherent barrier-free pedestrian system should be set up between buildings, outdoor venues, public green spaces, and urban roads.	/	Satisfied
		6.1.2	There should be a public transportation station within 500m of the pedestrian entrance and exit of the site or a special shuttle bus to contact the public transportation station.	/	Satisfied
		6.1.3	Electric vehicle charging facilities or the installation conditions for charging facilities should be equipped in the parking lot. Parking spaces for electric vehicles and barrier-free vehicles should be reasonably set up.	/	Satisfied
		6.1.4	Bicycle parking lots should be reasonably located and easily accessible.	/	Satisfied
		6.1.5	The construction equipment management system should have automatic monitoring and management functions.	/	Satisfied
		6.1.6	Buildings should be equipped with information network systems.	/	Satisfied
Scoring items	Travel and accessibility	6.2.1	The venue is conveniently connected to public transportation stations, with a total score of 8 points. The scores are awarded separately and accumulated according to the following rules: 1. The walking distance from the venue entrance to the public transportation station does not exceed 500m, or the walking distance to the rail transit station does not exceed 800m, 2 points are awarded. The walking distance from the venue entrance to the public transportation station does not exceed	8	8

			300m, or the walking distance to the rail transit station does not exceed 300m. If the distance is no more than 500m, 4 points are awarded. 2. There are public transportation stations with no less than 2 lines within a walking distance of 800m from the entrance and exit of the venue, 4 points are awarded.		
		6.2.2	The indoor and outdoor public areas of the building meet the design requirements for all ages, with a total score of 8 points, which are scored separately and accumulated according to the following rules: 1. The indoor public areas, outdoor public activity venues and roads of the building all meet the barrier-free design requirements, 3 points are awarded. 2. The external corners of walls, columns, etc. in the indoor public areas of the building are all rounded and equipped with safety grab bars or handrails, 3 points are awarded. 3. A barrier-free elevator that can accommodate stretchers is provided, 2 points are awarded.	8	6
	Service Facilities	6.2.3	Convenient public services are provided, with a total score of 10 points, based on the following rules: For public buildings that meet 3 of the following requirements, 5 points are provided. If they meet 5 of the following requirements, 10 points are provided: 1) The building is compatible with at least two socially oriented public service functions. 2) The building provides open public activity space to the public. 3) The number of parking spaces at electric vehicle charging piles accounts for no less than 10% of the total number of parking spaces. 4) There are public parking lots (garages) within 500m of the surrounding area. 5) The venue is not closed or the public pedestrian access within the venue is open to the public. For residential buildings that meet 4 of the following requirements, 5 points are awarded. If they meet 6 or more of the following requirements, 10 points are awarded. 1) The walking distance from the venue entrance to the kindergarten is no more than 300m. 2) The walking distance from the venue entrance to the primary school is no more than 500m. 3) The walking distance from the venue entrance to the middle school is no more than 1000m. 4) The walking distance from the venue entrance to the hospital is no more than 1000m. 5) The walking distance from the venue entrance to the mass cultural activity facilities is no more than 800m. 6) The walking distance from the venue entrance to the day care facility for the elderly is no more than 500m. 7) There are no less than 3 types of commercial service facilities within 500m of the site.	10	10
		6.2.4	Open spaces such as urban green spaces, squares, and public sports venues are within walking distance, with a total score of 5 points, and are scored separately and accumulated as follows: 1. The walking distance from the entrance and exit of the venue to urban parks, residential parks, and squares is no more than 300m, 3 points are awarded. 2. The walking distance to a medium-sized multi-functional sports venue is no more than 500m, 2 points are awarded.	5	3

		6.2.5	Fitness venues and spaces are set up reasonably, with a total score of 10 points. The scores are awarded separately and accumulated according to the following rules: 1. The outdoor fitness venue area is no less than 0.5% of the total land area, 3 points are awarded. 2. Set up a dedicated slow-motion fitness track with a width of no less than 1.25m and a length of no less than 1/4 of the perimeter of the red line of the land and no less than 100m, 2 points are awarded. 3. The area of the indoor fitness space is no less than 0.3% of the above-ground construction area and not less than 60 m^2, 3 points are awarded. 4. The stairwell has natural lighting and a good view and is no more than 15m away from the main entrance, 2 points are awarded.	10	0
	Smart operation	6.2.6	An automatic remote measurement system for classification and grading of energy consumption, and an energy management system to monitor, analyze and manage data have been set up, with a score of 8 points.	8	0
		6.2.7	An air quality monitoring system for PM10, PM2.5, and CO2 concentrations will be set up, with the functions of storing monitoring data for at least one year and displaying it in real time, 5 points are awarded.	5	0
		6.2.8	Various types of water remote measurement systems and water quality online monitoring systems have been set up, with a total score of 7 points. The scores are awarded separately and accumulated according to the following rules: 1. Set up a water consumption remote measurement system that can classify, hierarchically record, and statistically analyze various water use situations, 3 points are awarded. 2. Use measurement data to automatically detect, analyze, and rectify pipeline network leakage. If the pipeline leakage rate is less than 5%, 2 points are awarded. 3. Set up an online water quality monitoring system to monitor the water quality indicators of domestic drinking water, piped drinking water, swimming pool water, non-traditional water sources, and air-conditioning cooling water, record and save the water quality monitoring results, and make them available for user inquiry at any time, 2 points are awarded.	7	5
		6.2.9	An intelligent service system is provided, with a total score of 9 points, and is scored separately and accumulated according to the following rules: 1. Having at least 3 types of service functions such as home appliance control, lighting control, facility control, security alarm, environmental monitoring, and construction equipment control, 3 points are awarded. 2. Remote monitoring function is provided, 3 points are awarded. 3. The function of connecting to smart cities (urban areas and communities) is provided, with a score of 3 points.	9	0
	Property management	6.2.10	Formulate complete operating procedures and emergency plans for energy saving, water saving, material saving, and greening. Implement an energy resource management incentive mechanism,	/	/

			and implement it effectively, with a total score of 5 points. The scores are awarded separately and accumulated according to the following rules: 1. Relevant facilities have complete operating procedures and emergency plans, 2 points are awarded. 2. The property management agency's work assessment system includes an energy-saving and water-saving performance assessment incentive mechanism, 3 points are awarded.		
		6.2.11	The average daily water consumption of the building meets the water-saving water quota requirements in the current national standard "Water-saving Design Standard for Civil Buildings" GB 50555, with a total score of 5 points, and is scored according to the following rules: 1. The average daily water consumption is not greater than the average value of the water-saving water quota and the upper limit, 2 points are awarded. 2. If the average daily water consumption is greater than the lower limit of the water-saving water quota but not greater than the average, 3 points are awarded. 3. The average daily water consumption is not greater than the lower limit of the water-saving water quota, 5 points are awarded.	/	/
		6.2.12	Regularly evaluate the effects of green operations and optimize operations based on the results, with a total score of 12 points, which are scored separately and accumulated according to the following rules: 1.Develop technical solutions and plans for green building operation effect evaluation, 3 points are awarded. 2.Regularly inspect and adjust public facilities and equipment, and have records of inspection, debugging, operation, and calibration, with a full record, 3 points are awarded. 3. Regularly carry out energy-saving diagnostic assessments, formulate and implement optimization plans based on the assessment results, 4 points are awarded. 4.Regularly test and publicize the quality of various types of water, 2 points are awarded.	/	/
		6.2.13	Establish a green education publicity and practice mechanism, compile a manual for the use of green facilities, create a good green atmosphere, and conduct regular user satisfaction surveys, with a total score of 8 points, and the scores are awarded separately and accumulated according to the following rules: 1. Organize no less than 2 green education publicity and practice activities such as green building technology promotion, green life guidance, disaster emergency drills, etc. every year, and have activity records, 2 points are awarded. 2. Have a platform for green life display, experience or exchange and sharing, and provide users with green facility manuals, 3 points are awarded. 3. Conduct a user satisfaction survey on green performance once a year, and formulate, implement, and publicize improvement measures based on the survey results, 3 points are awarded.	/	/
Total score				70	**32**
7 Resource Saving					

Prerequisite items	/	7.1.1	Energy-saving design should be carried out on the building's shape, plane layout, spatial scale, envelope structure, etc. in combination with the natural conditions of the site and the functional requirements of the building and should comply with national requirements for energy-saving design.	/	Satisfied
		7.1.2	Measures should be taken to reduce the energy consumption of heating and air conditioning systems under partial load and partial space use, and should comply with the following regulations: 1. The orientation of the room should be distinguished, the heating and air-conditioning areas should be subdivided, and the system should be controlled by zone; 2 The partial load performance coefficient (IPLV) of the air-conditioning cooling source and the comprehensive refrigeration performance coefficient (SCOP) of the electric cooling source should comply with the provisions of the current national standard "Energy-saving Design Standard for Public Buildings" GB50189.	/	Satisfied
		7.1.3	The partition temperature should be set according to the function of the building space, and the temperature setting standard of the indoor transition zone space should be reasonably reduced.	/	Satisfied
		7.1.4	The lighting power density value of the main functional room should not be higher than the current value specified in the current national standard "Architectural Lighting Design Standard" GB 50034. The lighting system in the public area should implement energy-saving control such as zoning, timing, induction, etc. The lighting control in the daylighting areas should be independent of lighting controls in other areas.	/	Satisfied
		7.1.5	The energy consumption of various parts such as cold and heat sources, transmission and distribution systems, and lighting should be measured independently.	/	Satisfied
		7.1.6	Vertical elevators should adopt energy-saving measures such as group control, variable frequency speed regulation or energy feedback. Escalators should adopt energy-saving control measures such as variable frequency induction start.	/	Satisfied
		7.1.7	A water resources utilization plan should be formulated to coordinate the utilization of various water resources, and the following measures should be taken to save water resources: 1.Set up water metering devices according to usage, payment, or management units. 2.Water distribution branch pipes with water pressure greater than 0.2MPa at water points should be equipped with pressure reduction facilities but should meet the minimum working pressure requirements of water supply accessories. 3. Water-using appliances and equipment meet the requirements of water-saving products.	/	Satisfied
		7.1.8	Building structures with seriously irregular building shapes and layouts should not be used.	/	Satisfied
		7.1.9	The architectural elements should be simple, without a large number of decorative components, and should meet the following requirements: 1. The proportion of the cost of decorative components of residential buildings to the total construction cost should not be greater than 2%. 2. The proportion of the cost of decorative components of public buildings to the total construction cost should not be greater than 1%.	/	Satisfied
		7.1.10	The selected building materials should meet the following requirements:	/	Satisfied

			1. The proportion of the weight of building materials produced within 1,500km to the total weight of building materials should be greater than 60%. 2. The cast-in-place concrete should be ready-mixed concrete, and the construction mortar should be ready-mixed mortar.		
Scoring items	Land saving and land utilization	7.2.1	Economical and intensive use of land, with a total score of 20 points, and are scored according to the following rules: For residential buildings, they will be scored according to the rules of Table 7.2.1-1 based on the per capita residential land index of the neighborhood where they are located. For public buildings, they will be scored according to the rules of Table 7.2.1-2 based on the floor area ratio (R) of buildings with different functions.	20	20
		7.2.2	Rational develop and utilize underground space, with a total score of 12 points. The score is awarded based on the rules in Table 7.2.2. according to the underground space development and utilization indicators.	12	7
		7.2.3	Adopting mechanical parking facilities, underground parking garages or ground parking buildings, etc., with a total score of 8 points, based on the following rules: 1. If the ratio of the number of ground parking spaces in a residential building to the total number of residential units is less than 10%, 8 points are awarded. 2. The ratio of the ground parking area of a public building to its total construction land area is less than 8%, 8 points are awarded.	8	8
	Energy saving and energy utilization	7.2.4	Optimize the thermal performance of the building envelope, with a total score of 15 points. The scores are awarded according to the following rules: 1. If the thermal performance of the building envelope is better than the current national building energy-saving design standards, and the improvement reaches 5%, 5 points are awarded. If the improvement reaches 10%, 10 points are awarded. If the improvement reaches 15%, 15 points are awarded. 2. If the building heating and air conditioning load is reduced by 5%, 5 points are awarded. If it is reduced by 10%, 10 points are awarded. If it is reduced by 15%, 15 points are awarded.	15	5
		7.2.5	The energy efficiency of the cooling and heat source units of the heating and air conditioning system is better than the current national standard "Energy Saving Design Standard for Public Buildings" GB 50189 and the current relevant national standard energy efficiency limit value requirements, with a total score of 10 points, according to the rule of Table 7.2.5.	10	0
		7.2.6	Take effective measures to reasonably reduce the energy consumption of the terminal system and transmission and distribution system of the heating and air-conditioning system， with a total score of 5 points. The scores are awarded separately and accumulated according to the following rules: 1. The power consumption per unit air volume of the ventilation and air conditioning system fan is 20% lower than the current national standard "Energy Saving Design Standard for Public Buildings" GB 50189, 2 points are awarded. 2. The power consumption and heat transfer ratio of the hot water circulating pump in the central heating system and the power consumption and cold (heat) ratio of the circulating water pump in the	5	0

			air conditioning hot and cold-water system are lower than the values stipulated in the current national standard "Code for Design of Heating, Ventilation and Air Conditioning for Civil Buildings" GB 50736 20%, 3 points are awarded.		
		7.2.7	Adopting energy-saving electrical equipment and energy-saving control measures, with a total score of 10 points. The scores are awarded separately and accumulated according to the following rules: 1. The lighting power density of the main functional room reaches the target value specified in the current national standard "Architectural Lighting Design Standard" GB 50034, 5 points are awarded. 2. Artificial lighting in the daylighting area automatically adjusts with changes in natural illumination, 2 points are awarded. 3. Equipment such as lighting products, three-phase distribution transformers, water pumps, fans, etc., meet the energy-saving evaluation value requirements of the relevant national standards, 3 points are awarded.	10	0
		7.2.8	Take measures to reduce building energy consumption, 10 points are awarded. If the building energy consumption is reduced by 10% compared with the current national building energy-saving standards, 5 points are awarded. If the building energy consumption is reduced by 20%, 10 points are awarded.	10	0
		7.2.9	Reasonably utilize the renewable energy based on local climate and natural resource conditions, with a total score of 10 points, according to the rules in Table 7.2.9.	10	0
	Water saving and water resource utilization	7.2.10	Adopt sanitary appliances with a higher water efficiency level, with a total score of 15 points. The scores are awarded according to the following rules: 1. The water efficiency level of all sanitary appliances reaches level 2, 8 points are awarded. 2. If the water efficiency level of more than 50% of the sanitary appliances reaches level 1 and the other reaches level 2, 12 points are awarded. 3. The water efficiency level of all sanitary appliances reaches level 1, 15 points are awarded.	15	8
		7.2.11	Green irrigation and air-conditioning cooling water systems adopt water-saving equipment or technology, with a total score of 12 points. The scores are awarded separately and accumulated according to the following rules: 1. Water-saving equipment or technology is used for greening irrigation and is scored according to the following rules: 1) Use water-saving irrigation system, 4 points are awarded. 2) On the basis of using a water-saving irrigation system, set up water-saving control measures such as soil moisture sensors and automatic shut-off devices in rainy days, or plant plants that do not require permanent irrigation, 6 points are awarded. 2. The air-conditioning cooling water system adopts water-saving equipment or technology and is scored according to the following rules: 1) The circulating cooling water system adopts water treatment measures, enlarging the water collection pan, setting up a balance pipe or a balance water tank, etc. to avoid cooling water overflow when the cooling water pump stops, 3 points are awarded.	12	10

			2) Use cooling technology without evaporative water consumption, 6 points are awarded.		
		7.2.12	Combine rainwater comprehensive utilization facilities to create an outdoor landscape water body. The amount of water replenished by rainwater for the outdoor landscape water body is greater than 60% of the evaporation of the water body, and ecological water treatment technology is used to ensure the water quality. The total score is 8 points, respectively awarded and accumulated according to the following rules: 1. For rainwater entering outdoor landscape water bodies, ecological facilities are used to reduce runoff pollution, 4 points are awarded. 2. Use aquatic animals and plants to ensure the water quality of outdoor landscape water bodies, 4 points are awarded.	8	0
		7.2.13	Adopt non-traditional water sources, with a total score of 15 points. The scores are awarded separately and accumulated according to the following rules: 1. If the water consumption of non-traditional water sources for green irrigation, garage and road washing, and car washing accounts for no less than 40% of the total water consumption, 3 points are awarded. If no less than 60% is used, 5 points are awarded. 2. If the water consumption of non-traditional water sources for toilet flushing accounts for not less than 30% of the total water consumption, 3 points are awarded. If the proportion of non-traditional water sources used for toilet flushing is not less than 50%, 5 points are awarded. 3. If the water consumption of non-traditional water sources for cooling water replenishment accounts for not less than 20% of the total water consumption, 3 points are awarded. If the water consumption is not less than 40%, 5 points are awarded.	15	0
	Material saving and green building materials	7.2.14	The integrated design and construction of civil engineering and decoration engineering are implemented in all areas of the building, 8 points are awarded.	8	8
		7.2.15	Reasonably select building structural materials and components, with a total score of 10 points, based on the following rules: 1. Concrete structures are scored separately and accumulated according to the following rules: 1) The application proportion of steel bars with strength grade 400MPa and above reaches 85%, 5 points are awarded. 2) The concrete vertical load-bearing structure adopts a strength grade of not less than C50. The proportion of concrete used in the vertical load-bearing structure reaches 50% of the total concrete in the vertical load-bearing structure, 5 points are awarded. 2. Steel structures are scored separately and accumulated according to the following rules: 1) If the proportion of Q345 and above high-strength steel in the total steel reaches 50%, 3 points are awarded. If it reaches 70%, 4 points are awarded. 2) Off-site welding nodes such as bolted connections account for 50% of all on-site connection and splicing nodes, 4 points are awarded. 3) The use of roof panels that require no support during construction, 2 points are awarded.	10	5

			3. Hybrid structure: The concrete structure part and the steel structure part are evaluated according to paragraphs 1 and 2 of this provision respectively, and the score are calculated as the average of each score.		
		7.2.16	The building decoration uses industrialized interior parts, with a total score of 8 points, and is awarded according to the following rules: 1. If the proportion of industrialized interior parts used in building decoration reaches more than 50% of similar parts, 1 type is awarded 3 points. 2 If the proportion of industrialized interior parts used in building decoration reaches more than 50% of similar parts, 3 types are awarded 5 points. 3. If the proportion of industrialized interior parts used in building decoration reaches more than 50% of similar parts, over 3 types are awarded 8 points.	8	0
		7.2.17	Select recyclable materials, reusable materials, and waste-using building materials, with a total score of 12 points, are awarded separately and accumulated according to the following rules: 1.The proportion of recyclable materials and reusable materials is scored according to the following rules: 1) If residential buildings reach 6% or public buildings reach 10%, 3 points are awarded. 2) If residential buildings reach 10% or public buildings reach 15%, 6 points are awarded. 2. The selection and proportion of waste-recycling building materials are scored according to the following rules: 1) Choose a building material that uses waste, and its proportion of the usage of similar building materials is not less than 50%, 3 points are awarded. 2) Select two or more recycled building materials, each accounting for no less than 30% of the same type of building materials, 6 points are awarded.	12	0
		7.2.18	Select green building materials, with a total score of 12 points, and are awarded according to the following rules: 1. The application proportion of green building materials is not less than 30%, 4 points are awarded. 2. The application proportion of green building materials is not less than 50%, 8 points are awarded. 3. The application proportion of green building materials is not less than 70%, 12 points are awarded.	12	0
Total score				200	**71**
8 Environment Livability					
Prerequisite items	/	8.1.1	The building planning and layout should meet the sun lighting standards, and the sun lighting standards of surrounding buildings should not be reduced.	/	Satisfied
		8.1.2	The outdoor thermal environment should meet the requirements of current relevant national standards.	/	Satisfied
		8.1.3	The green space to be constructed should comply with the requirements of the local urban and rural planning, and the greening method should be reasonably selected. Plant planting should adapt to the local climate and soil and should be non-toxic and easy to maintain. The soil covering depth and drainage capacity of the planting area should meet the needs of plant growth and should be adopted multi-layer greening method.	/	Satisfied

		8.1.4	The vertical design of the site should be conducive to the collection or discharge of rainwater, and the infiltration, retention or reuse of rainwater should be effectively organized. For sites larger than 10hm2, special designs for rainwater control and utilization should be carried out.	/	Satisfied
		8.1.5	A signage system should be installed inside and outside the building to facilitate identification and use.	/	Satisfied
		8.1.6	Pollution sources that emit excessive emissions should not be allowed on the site.	/	Satisfied
		8.1.7	Domestic garbage should be collected in categories, and the settings of garbage containers and collection points should be reasonable and coordinated with the surrounding landscape.	/	Satisfied
Scoring items	Site ecological landscape	8.2.1	Fully protect or restore the ecological environment of the site, and rationally layout the buildings and landscapes, with a total score of 10 points. The scores are awarded according to the following rules: 1. Protect the original natural waters, wetlands, vegetation, etc. within the site and maintaining the continuity of the ecosystem within the site and the ecosystem outside the site, 10 points are awarded. 2. Adopt ecological compensation measures such as recycling and utilizing clean surface soil, 10 points are awarded. 3. Take other ecological restoration or compensation measures based on the actual conditions of the site, 10 points are awarded.	10	0
		8.2.2	Plan the surface and roof rainwater runoff of the site and control the total amount of rainwater discharged from the site, with a total score of 10 points. If the total annual runoff control rate of the site reaches 55%, 5 points are awarded. If it reaches 70%, 10 points are awarded.	10	10
		8.2.3	Make full use of the site space to set up green land, with a total score of 16 points, and is awarded based on the following rules: Residential buildings are scored separately and cumulatively according to the following rules: 1) If the green space rate reaches 105% of the planning indicator or above, 10 points are awarded. 2) The area of concentrated green space per person in the neighborhood where the residential building is located, a maximum score of 6 points is awarded according to the rules in Table 8.2.3. Public buildings are scored separately and accumulated according to the following rules: 1) If the green space rate of public buildings reaches the planning indicator of 105% or above, 10 points are awarded. 2) Green space open to the public, 6 points are awarded.	16	0
		8.2.4	The outdoor smoking area has a reasonable layout, with a total score of 9 points, which are scored separately and accumulated according to the following rules: 1. The outdoor smoking area is arranged in the downwind direction of the dominant wind at the main entrance and exit of the building. The distance from all building entrances and exits, fresh air inlets and openable window sash is not less than 8m, and the distance from the activity venue for children and the elderly is not less than 8m, 5 points are awarded. 2. The outdoor smoking area is arranged in combination with green plants, and the seats and garbage cans with cigarette butt collection are reasonably arranged. The guidance signs from the main	9	9

			entrance and exit of the building to the outdoor smoking area are complete and the positioning signs are eye-catching. The smoking area is equipped with warning signs that smoking is harmful to health, 4 points are awarded.		
		8.2.5	Make use of the site space to set up green rainwater infrastructure, with a total score of 15 points, and the scores are awarded separately and accumulated according to the following rules: 1. If the sum of the area of green spaces and water bodies with the function of regulating and storing rainwater, such as sunken green spaces and rain gardens, accounts for 40% of the green space area, 3 points are awarded. If it reaches 60%, 5 points are awarded. 2. Connect and guide no less than 80% of roof rainwater into ground ecological facilities, 3 points are awarded. 3. Connect and guide no less than 80% of road rainwater into ground ecological facilities, 4 points are awarded. 4. If the proportion of permeable paving area in the hard paved floor reaches 50%, 3 points are awarded.	15	0
	Outdoor physical environment	8.2.6	The environmental noise in the venue is better than the requirements of the current national standard "Acoustic Environment Quality Standard" GB 3096, with a total score of 10 points and is awarded according to the following rules: 1. If the environmental noise value is greater than the standard limit of the Class 2 acoustic environment functional area and less than or equal to the standard limit of the Class 3 acoustic environment functional area, 5 points are awarded. 2. If the environmental noise value is less than or equal to the standard limit of Class 2 acoustic environment functional area, 10 points are awarded.	10	10
		8.2.7	The architectural and lighting design avoids light pollution, with a total score of 10 points, which are scored separately and accumulated according to the following rules: 1. The visible light reflectance of the glass curtain wall and the impact of reflected light on the surrounding environment comply with the provisions of "Optical Performance of Glass Curtain Walls" GB/T 18091, 5 points are awarded. 2. The limits on light pollution from outdoor nightscape lighting comply with the current national standard "Specifications for Limitation of Interfering Light from Outdoor Lighting" GB/T 35626 and the current industry standard "Code for Design of Urban Nightscape Lighting" JGJ/T 163, 5 points are awarded.	10	10
		8.2.8	The wind environment inside the site is conducive to outdoor walking, comfortable activities, and natural ventilation of the building, with a total score of 10 points, which are scored separately and accumulated according to the following rules: 1. Under typical wind speed and direction conditions in winter, scores are awarded and accumulated according to the following rules:	10	5

			1) The wind speed in the pedestrian area around the building is less than 5m/s at a height of 1.5m from the ground, the wind speed in the outdoor rest area and children's entertainment area is less than 2m/s, and the outdoor wind speed amplification factor is less than 2, 3 points are awarded. 2) Except for the first row of buildings facing the wind, the wind pressure difference between the windward and leeward sides of the building is not greater than 5Pa, 2 points are awarded. 2. Under typical wind speed and direction conditions in transition season and summer, scores will be awarded separately and accumulated according to the following rules: 1) If there is no vortex or windless area in the human activity area of the venue, 3 points are awarded. 2) If the wind pressure difference between the indoor and outdoor surfaces of more than 50% of openable windows is greater than 0.5Pa, 2 points are awarded.		
		8.2.9	Take measures to reduce the heat island intensity, with a total score of 10 points, which are awarded separately and accumulated according to the following rules: 1. The proportion of the area of outdoor activity venues such as trails, recreation fields, courtyards, squares, etc. outside the shadow area of the building that is equipped with shading measures such as trees and flower trellises. Residential buildings reach 30% and public buildings reach 10%, 2 points are awarded. Residential buildings reaching 50% and public buildings reaching 20%, 3 points are awarded. 2. For motor vehicle lanes outside the building shadow area on the site, if the solar radiation reflection coefficient of the road surface is not less than 0.4 or the length of the road section with street trees with a large shading area exceeds 70%, 3 points are awarded. 3. When the total green area of the roof, the horizontal projection area of the solar panel and the roof area with a solar radiation reflection coefficient of not less than 0.4 reach 75%, 4 points are awarded.	10	0
Total score				100	**44**
9 Promotion and Innovation					
General provisions	/	9.1.1	When evaluating green buildings, improvements and innovation items should be evaluated in accordance with the provisions of this chapter.	/	/
		9.1.2	The score for the improvement and innovation items is the sum of the scores for the bonus items. When the score is greater than 100 points, it should be taken as 100 points.	/	/
Bonus items	/	9.2.1	Take measures to further reduce energy consumption of building heating and air conditioning systems, with a total score of 30 points. If the energy consumption of the building heating and air conditioning system is reduced by 40% compared with the current national building energy conservation standards, 10 points are awarded. For each additional 10% reduction, an additional 5 points are awarded, up to a maximum of 30 points.	30	0
		9.2.2	Adopt an architectural style design suitable for regional characteristics and inherit regional architectural culture according to local conditions, with a score of 20 points.	20	0
		9.2.3	Reasonably select the abandoned sites for construction or make full use of old buildings that can still be used, with a score of 8 points.	8	0

		9.2.4	The green content rate of the site is not less than 3.0, with a total score of 5 points, and are scored according to the following rules: 1. The calculated value of the green space rate of the venue is not less than 3.0, 3 points are awarded. 2. The measured value of the green space rate of the venue is not less than 3.0, 5 points are awarded.	5	0
		9.2.5	Adopt the structural system and building components that meet the requirements of industrialized construction, 10 points are awarded, and the scores are awarded according to the following rules: 1. If the main structure adopts steel structure or wooden structure, 10 points are awarded. 2. If the main structure adopts a prefabricated concrete structure. If the proportion of concrete used in the above-ground prefabricated components to the total concrete volume reaches 35%, 5 points are awarded. If it reaches 50%, 10 points are awarded.	10	0
		9.2.6	Apply Building Information Modeling (BIM) technology, with a total score of 15 points, and the score is based on the following rules: 1. Applied in one of the planning and design, construction and operation and maintenance stages of the building, 5 points are awarded. 2. Application in two stages of the planning and design, construction and operation and maintenance stages of the building, 10 points are awarded. 3. Application in the three stages of planning and design, construction and operation and maintenance of the building, 15 points are awarded.	15	5
		9.2.7	Carry out building carbon emission calculation and analysis and take measures to reduce the carbon emission intensity per unit building area, with a score of 12 points.	12	12
		9.2.8	Construction and management are carried out in accordance with the requirements of green construction, with a total score of 20 points, which are scored separately and accumulated according to the following rules: 1. Obtain the green construction excellent grade or green construction demonstration project certification, 8 points are awarded. 2. Take measures to reduce the loss of ready-mixed concrete and reduce the loss rate to 1.0%, 4 points are awarded. 3. Take measures to reduce the loss of steel bars during on-site processing, and reduce the loss rate to 1.5%, 4 points are awarded. 4. The cast-in-place concrete components use aluminum membrane and other formwork systems that do not require wall painting, 4 points are awarded.	20	0
		9.2.9	Adopt construction project quality latent defect insurance products, with a total score of 20 points, which are scored separately and accumulated according to the following rules: 1. The insurance coverage includes quality problems of foundation engineering, main structure engineering, roof waterproofing engineering and other civil engineering projects, 10 points are awarded.	20	0

			2. The insurance coverage includes decoration projects, installation projects of electrical pipelines, water supply and drainage pipelines, and quality issues of heating and cooling system projects, 10 points are awarded.		
		9.2.10	Adopt other innovations such as saving energy resources, protecting the ecological environment, ensuring safety and health, smart and friendly operation, inheriting history and culture, etc., and have obvious benefits, with a total score of 40 points. Each item taken is worth 10 points, up to a maximum of 40 points.	40	0
Total score（≤100 points）				100	**17**

(Source: the investigated green building consulting company in Shenzhen)

Appendix C. Cash flow statement for Merbau A during O&M stage over a 50-year life cycle

Life cycle		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)
Net cash flow (£)		2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67
Life cycle		**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)
Net cash flow (£)		2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67
Life cycle		**T21**	**T22**	**T23**	**T24**	**T25**	**T26**	**T27**	**T28**	**T29**	**T30**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-

	Protective coatings (Transportation costs included) (£)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)
Net cash flow (£)		2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67
Life cycle		**T31**	**T32**	**T33**	**T34**	**T35**	**T36**	**T37**	**T38**	**T39**	**T40**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	(618.66)
	Protective coatings (Transportation costs included) (£)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)
Net cash flow (£)		2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,357.01
Life cycle		**T41**	**T42**	**T43**	**T44**	**T45**	**T46**	**T47**	**T48**	**T49**	**T50**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	(298.19)	-
Net cash flow (£)		2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	2,975.67	3,273.86

Appendix D. Cash flow statement for Merbau B during O&M stage over a 50-year life cycle

Life cycle		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)
Net cash flow (£)		2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32
Life cycle		**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)
Net cash flow (£)		2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32
Life cycle		**T21**	**T22**	**T23**	**T24**	**T25**	**T26**	**T27**	**T28**	**T29**	**T30**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-

	Protective coatings (Transportation costs included) (£)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)
Net cash flow (£)		2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32
Life cycle		**T31**	**T32**	**T33**	**T34**	**T35**	**T36**	**T37**	**T38**	**T39**	**T40**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	(1,557.70)
	Protective coatings (Transportation costs included) (£)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)
Net cash flow (£)		2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	(1,019.62)
Life cycle		**T41**	**T42**	**T43**	**T44**	**T45**	**T46**	**T47**	**T48**	**T49**	**T50**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	(742.92)	-
Net cash flow (£)		2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	2,577.32	3,320.24

Appendix E. Cash flow statement for Aluminum A during O&M stage over a 50-year life cycle

Life cycle		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Life cycle		**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	(12,217.25)	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)					(784.63)					
Net cash flow (£)		3,273.86	3,273.86	3,273.86	3,273.86	(9,728.02)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Life cycle		**T21**	**T22**	**T23**	**T24**	**T25**	**T26**	**T27**	**T28**	**T29**	**T30**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	(12,217.25)

	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	(784.63)
Net cash flow (£)		3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	(9,728.02)
Life cycle		**T31**	**T32**	**T33**	**T34**	**T35**	**T36**	**T37**	**T38**	**T39**	**T40**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Life cycle		**T41**	**T42**	**T43**	**T44**	**T45**	**T46**	**T47**	**T48**	**T49**	**T50**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	(12,217.25)	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	(784.63)	-	-	-	-	-
Net cash flow (£)		3,273.86	3,273.86	3,273.86	3,273.86	(9,728.02)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86

Appendix F. Cash flow statement for Aluminum B during O&M stage over a 50-year life cycle

Life cycle		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Life cycle		**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	(30,441.59)	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	(1,954.86)	-	-	-	-	-
Net cash flow (£)		3,320.24	3,320.24	3,320.24	3,320.24	(29,076.21)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Life cycle		**T21**	**T22**	**T23**	**T24**	**T25**	**T26**	**T27**	**T28**	**T29**	**T30**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation	-	-	-	-	-	-	-	-	-	(30,441.59)

	costs included) (£)										
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	(1,954.86)
Net cash flow (£)		3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	(29,076.21)
Life cycle		**T31**	**T32**	**T33**	**T34**	**T35**	**T36**	**T37**	**T38**	**T39**	**T40**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Life cycle		**T41**	**T42**	**T43**	**T44**	**T45**	**T46**	**T47**	**T48**	**T49**	**T50**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	(30,441.59)	-	-	-	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	(1,954.86)	-	-	-	-	-
Net cash flow (£)		3,320.24	3,320.24	3,320.24	3,320.24	(29,076.21)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24

Appendix G. Cash flow statement for Polycarbonate A during O&M stage over a 50-year life cycle

Life cycle		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	(2,447.25)	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	826.61	3,273.86	3,273.86
Life cycle		**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	(2,447.25)	-	-	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	826.61	3,273.86	3,273.86	3,273.86	3,273.86
Life cycle		**T21**	**T22**	**T23**	**T24**	**T25**	**T26**	**T27**	**T28**	**T29**	**T30**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation	-	-	-	(2,447.25)	-	-	-	-	-	-

	costs included) (£)										
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,273.86	3,273.86	3,273.86	826.61	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Life cycle		**T31**	**T32**	**T33**	**T34**	**T35**	**T36**	**T37**	**T38**	**T39**	**T40**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	(2,447.25)	-	-	-	-	-	-	-	(2,447.25)
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,273.86	826.61	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	826.61
Life cycle		**T41**	**T42**	**T43**	**T44**	**T45**	**T46**	**T47**	**T48**	**T49**	**T50**
Cash inflow	Savings of electricity expenditure (£)	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	(2,447.25)	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	3,273.86	826.61	3,273.86	3,273.86

Appendix H. Cash flow statement for Polycarbonate B during O&M stage over a 50-year life cycle

Life cycle		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	(6,098.24)	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	(2,778)	3,320.24	3,320.24
Life cycle		**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**	**T19**	**T20**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	(6,098.24)	-	-	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	(2,778)	3,320.24	3,320.24	3,320.24	3,320.24
Life cycle		**T21**	**T22**	**T23**	**T24**	**T25**	**T26**	**T27**	**T28**	**T29**	**T30**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation	-	-	-	(6,098.24)	-	-	-	-	-	-

	costs included) (£)										
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,320.24	3,320.24	3,320.24	(2,778.00)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Life cycle		**T31**	**T32**	**T33**	**T34**	**T35**	**T36**	**T37**	**T38**	**T39**	**T40**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	(6,098.24)	-	-	-	-	-	-	-	(6,098.24)
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,320.24	(2,778.00)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	(2,778.00)
Life cycle		**T41**	**T42**	**T43**	**T44**	**T45**	**T46**	**T47**	**T48**	**T49**	**T50**
Cash inflow	Savings of electricity expenditure (£)	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24
Cash outflow	Materials (Transportation costs included) (£)	-	-	-	-	-	-	-	(6,098.24)	-	-
	Protective coatings (Transportation costs included) (£)	-	-	-	-	-	-	-	-	-	-
Net cash flow (£)		3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	3,320.24	(2,778.00)	3,320.24	3,320.24

Appendix I. CO_2 emission amount of building materials production stage (C_{SC}) regarding Merbau A made fixed external shading devices (50-year building lifespan)

Construction material	Total usage of material	Unit	CO_2 emission factor ($kgCO_2e$/unit)	CO_2 emission amount (tCO_2e)
Concrete	1,466.84	m^3	340.00	498.73
Rebar	173.20	t	2,340.00	405.29
Section steel	2.14	t	2,365.00	5.06
Cement	85.53	t	735.00	62.86
Ready mixed mortar	378.47	t	370.00	140.03
Sand	171.06	m^3	3.00	0.51
Extruded polystyrene foam board	71.40	m^3	534.00	38.13
NEA insulation leveling gel	56.12	m^3	534.00	29.97
Building blocks	186.03	m^3	349.00	64.92
Brick	190.30	m^3	336.00	63.94
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	283.59	m^2	129.50	36.72
Insulation door (multifunctional door)	78.16	m^2	48.30	3.78
Ceramics	2,225.91	m^2	19.50	43.41
Coating	8.55	t	6,550.00	56.00
Cable	222.38	kg	94.10	20.93
Pipes	2,779.72	kg	3.60	10.01
Merbau	1.18	m^3	178.00	0.21
Water-based coating	2.40	t	231.00	0.55
Sum of C_{SC}				1,481.05

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database.)

Appendix J. CO_2 emission amount of building materials production stage (C_{SC}) regarding Merbau B made fixed external shading devices (50-year building lifespan)

Construction material	Total usage of material	Unit	CO_2 emission factor ($kgCO_2e$/unit)	CO_2 emission amount (tCO_2e)
Concrete	1,466.84	m^3	340.00	498.73
Rebar	173.20	t	2,340.00	405.29
Section steel	2.14	t	2,365.00	5.06
Cement	85.53	t	735.00	62.86
Ready mixed mortar	378.47	t	370.00	140.03
Sand	171.06	m^3	3.00	0.51
Extruded polystyrene foam board	71.40	m^3	534.00	38.13
NEA insulation leveling gel	56.12	m^3	534.00	29.97
Building blocks	186.03	m^3	349.00	64.92
Brick	190.30	m^3	336.00	63.94
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	283.59	m^2	129.50	36.72
Insulation door (multifunctional door)	78.16	m^2	48.30	3.78
Ceramics	2,225.91	m^2	19.50	43.41
Coating	8.55	t	6,550.00	56.00
Cable	222.38	kg	94.10	20.93
Pipes	2,779.72	kg	3.60	10.01
Merbau	2.97	m^3	178.00	0.53
Water-based coating	5.99	t	231.00	1.38
Sum of C_{SC}				1,482.20

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database.)

Appendix K. CO_2 emission amount of building materials production stage (C_{SC}) regarding Aluminum A made fixed external shading devices (50-year building lifespan)

Construction material	Total usage of material	Unit	CO_2 emission factor (kgCO_2e/unit)	CO_2 emission amount (tCO_2e)
Concrete	1,466.84	m^3	340.00	498.73
Rebar	173.20	t	2,340.00	405.29
Section steel	2.14	t	2,365.00	5.06
Cement	85.53	t	735.00	62.86
Ready mixed mortar	378.47	t	370.00	140.03
Sand	171.06	m^3	3.00	0.51
Extruded polystyrene foam board	71.40	m^3	534.00	38.13
NEA insulation leveling gel	56.12	m^3	534.00	29.97
Building blocks	186.03	m^3	349.00	64.92
Brick	190.30	m^3	336.00	63.94
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	283.59	m^2	129.50	36.72
Insulation door (multifunctional door)	78.16	m^2	48.30	3.78
Ceramics	2,225.91	m^2	19.50	43.41
Coating	8.55	t	6,550.00	56.00
Cable	222.38	kg	94.10	20.93
Pipes	2,779.72	kg	3.60	10.01
Raw aluminum	6.41	t	18,790.00	120.44
Fluorocarbon coating	0.19	t	3,600.00	0.68
Sum of C_{SC}				1,601.42

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database.)

Appendix L. CO_2 emission amount of building materials production stage (C_{SC}) regarding Aluminum B made fixed external shading devices (50-year building lifespan)

Construction material	Total usage of material	Unit	CO_2 emission factor ($kgCO_2e$/unit)	CO_2 emission amount (tCO_2e)
Concrete	1,466.84	m^3	340.00	498.73
Rebar	173.20	t	2,340.00	405.29
Section steel	2.14	t	2,365.00	5.06
Cement	85.53	t	735.00	62.86
Ready mixed mortar	378.47	t	370.00	140.03
Sand	171.06	m^3	3.00	0.51
Extruded polystyrene foam board	71.40	m^3	534.00	38.13
NEA insulation leveling gel	56.12	m^3	534.00	29.97
Building blocks	186.03	m^3	349.00	64.92
Brick	190.30	m^3	336.00	63.94
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	283.59	m^2	129.50	36.72
Insulation door (multifunctional door)	78.16	m^2	48.30	3.78
Ceramics	2,225.91	m^2	19.50	43.41
Coating	8.55	t	6,550.00	56.00
Cable	222.38	kg	94.10	20.93
Pipes	2,779.72	kg	3.60	10.01
Raw aluminum	16.14	t	18,790.00	303.27
Fluorocarbon coating	0.48	t	3,600.00	1.73
Sum of C_{SC}				1,785.29

*Note: 1t equals to 1,000kg.

(Source: CEEB 2024 database.)

Appendix M. CO_2 emission amount of building materials production stage (C_{SC}) regarding Polycarbonate A made fixed external shading devices (50-year building lifespan)

Construction material	Total usage of material	Unit	CO_2 emission factor ($kgCO_2e$/unit)	CO_2 emission amount (tCO_2e)
Concrete	1,466.84	m^3	340.00	498.73
Rebar	173.20	t	2,340.00	405.29
Section steel	2.14	t	2,365.00	5.06
Cement	85.53	t	735.00	62.86
Ready mixed mortar	378.47	t	370.00	140.03
Sand	171.06	m^3	3.00	0.51
Extruded polystyrene foam board	71.40	m^3	534.00	38.13
NEA insulation leveling gel	56.12	m^3	534.00	29.97
Building blocks	186.03	m^3	349.00	64.92
Brick	190.30	m^3	336.00	63.94
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	283.59	m^2	129.50	36.72
Insulation door (multifunctional door)	78.16	m^2	48.30	3.78
Ceramics	2,225.91	m^2	19.50	43.41
Coating	8.55	t	6,550.00	56.00
Cable	222.38	kg	94.10	20.93
Pipes	2,779.72	kg	3.60	10.01
Polycarbonate	4.95	t	1,370.50	6.78
Sum of C_{SC}				1,487.07

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database.)

Appendix N. CO_2 emission amount of building materials production stage (C_{SC}) regarding Polycarbonate B made fixed external shading devices (50-year building lifespan)

Construction material	Total usage of material	Unit	CO_2 emission factor ($kgCO_2e$/unit)	CO_2 emission amount (tCO_2e)
Concrete	1,466.84	m^3	340.00	498.73
Rebar	173.20	t	2,340.00	405.29
Section steel	2.14	t	2,365.00	5.06
Cement	85.53	t	735.00	62.86
Ready mixed mortar	378.47	t	370.00	140.03
Sand	171.06	m^3	3.00	0.51
Extruded polystyrene foam board	71.40	m^3	534.00	38.13
NEA insulation leveling gel	56.12	m^3	534.00	29.97
Building blocks	186.03	m^3	349.00	64.92
Brick	190.30	m^3	336.00	63.94
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	283.59	m^2	129.50	36.72
Insulation door (multifunctional door)	78.16	m^2	48.30	3.78
Ceramics	2,225.91	m^2	19.50	43.41
Coating	8.55	t	6,550.00	56.00
Cable	222.38	kg	94.10	20.93
Pipes	2,779.72	kg	3.60	10.01
Polycarbonate	12.46	t	1,370.50	17.08
Sum of C_{SC}				1,497.36

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database.)

Appendix O. CO_2 emission amount of building materials transportation stage (C_{YS}) regarding Merbau A made fixed external shading devices (50-year building lifespan)

Construction material	Total weight of material (t)	Transportation distance (km)	CO_2 emission factor ($kgCO_2e/t{\cdot}km$)	CO_2 emission amount (tCO_2e)
Concrete	3,461.73	40	0.115	15.92
Rebar	173.20	500	0.115	9.96
Section steel	2.14	500	0.115	0.12
Cement	85.53	500	0.115	4.92
Ready mixed mortar	378.47	40	0.115	1.74
Sand	273.70	500	0.115	15.74
Extruded polystyrene foam board	2.86	500	0.115	0.16
NEA insulation leveling gel	24.13	500	0.115	1.39
Building blocks	186.03	500	0.115	10.70
Brick	275.94	500	0.115	15.87
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	5.67	500	0.115	0.33
Insulation door (multifunctional door)	2.34	500	0.115	0.13
Ceramics	66.78	500	0.115	3.84
Coating	8.55	500	0.104	0.44
Cable	0.22	500	0.334	0.04
Pipes	2.78	500	0.115	0.16
Merbau	1.18	500	0.334	0.20
Water-based coating	2.40	500	0.334	0.40
Sum of the C_{YS}				82.06

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database.)

Appendix P. CO_2 emission amount of building materials transportation stage (C_{YS}) regarding Merbau B made fixed external shading devices (50-year building lifespan)

Construction material	Total weight of material (t)	Transportation distance (km)	CO_2 emission factor ($kgCO_2e/t \cdot km$)	CO_2 emission amount (tCO_2e)
Concrete	3,461.73	40	0.115	15.92
Rebar	173.20	500	0.115	9.96
Section steel	2.14	500	0.115	0.12
Cement	85.53	500	0.115	4.92
Ready mixed mortar	378.47	40	0.115	1.74
Sand	273.70	500	0.115	15.74
Extruded polystyrene foam board	2.86	500	0.115	0.16
NEA insulation leveling gel	24.13	500	0.115	1.39
Building blocks	186.03	500	0.115	10.70
Brick	275.94	500	0.115	15.87
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	5.67	500	0.115	0.33
Insulation door (multifunctional door)	2.34	500	0.115	0.13
Ceramics	66.78	500	0.115	3.84
Coating	8.55	500	0.104	0.44
Cable	0.22	500	0.334	0.04
Pipes	2.78	500	0.115	0.16
Merbau	2.97	500	0.334	0.50
Water-based coating	5.99	500	0.334	1.00
Sum of C_{YS}				82.96

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database.)

Appendix Q. CO_2 emission amount of building materials transportation stage (C_{YS}) regarding Aluminum A made fixed external shading devices (50-year building lifespan)

Construction material	Total weight of material (t)	Transportation distance (km)	CO_2 emission factor ($kgCO_2e/t \cdot km$)	CO_2 emission amount (tCO_2e)
Concrete	3,461.73	40	0.115	15.92
Rebar	173.20	500	0.115	9.96
Section steel	2.14	500	0.115	0.12
Cement	85.53	500	0.115	4.92
Ready mixed mortar	378.47	40	0.115	1.74
Sand	273.70	500	0.115	15.74
Extruded polystyrene foam board	2.86	500	0.115	0.16
NEA insulation leveling gel	24.13	500	0.115	1.39
Building blocks	186.03	500	0.115	10.70
Brick	275.94	500	0.115	15.87
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	5.67	500	0.115	0.33
Insulation door (multifunctional door)	2.34	500	0.115	0.13
Ceramics	66.78	500	0.115	3.84
Coating	8.55	500	0.104	0.44
Cable	0.22	500	0.334	0.04
Pipes	2.78	500	0.115	0.16
Raw aluminum	6.41	500	0.115	0.37
Fluorocarbon coating	0.19	500	0.334	0.03
Sum of C_{YS}				81.86

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database.)

Appendix R. CO_2 emission amount of building materials transportation stage (C_{YS}) regarding Aluminum B made fixed external shading devices (50-year building lifespan)

Construction material	Total weight of material (t)	Transportation distance (km)	CO_2 emission factor ($kgCO_2e/t \cdot km$)	CO_2 emission amount (tCO_2e)
Concrete	3,461.73	40	0.115	15.92
Rebar	173.20	500	0.115	9.96
Section steel	2.14	500	0.115	0.12
Cement	85.53	500	0.115	4.92
Ready mixed mortar	378.47	40	0.115	1.74
Sand	273.70	500	0.115	15.74
Extruded polystyrene foam board	2.86	500	0.115	0.16
NEA insulation leveling gel	24.13	500	0.115	1.39
Building blocks	186.03	500	0.115	10.70
Brick	275.94	500	0.115	15.87
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	5.67	500	0.115	0.33
Insulation door (multifunctional door)	2.34	500	0.115	0.13
Ceramics	66.78	500	0.115	3.84
Coating	8.55	500	0.104	0.44
Cable	0.22	500	0.334	0.04
Pipes	2.78	500	0.115	0.16
Raw aluminum	16.14	500	0.104	0.84
Fluorocarbon coating	0.48	500	0.334	0.08
Sum of C_{YS}				82.38

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database.)

Appendix S. CO_2 emission amount of building materials transportation stage (C_{YS}) regarding Polycarbonate A made fixed external shading devices (50-year building lifespan)

Construction material	Total weight of material (t)	Transportation distance (km)	CO_2 emission factor ($kgCO_2e/t \cdot km$)	CO_2 emission amount (tCO_2e)
Concrete	3,461.73	40	0.115	15.92
Rebar	173.20	500	0.115	9.96
Section steel	2.14	500	0.115	0.12
Cement	85.53	500	0.115	4.92
Ready mixed mortar	378.47	40	0.115	1.74
Sand	273.70	500	0.115	15.74
Extruded polystyrene foam board	2.86	500	0.115	0.16
NEA insulation leveling gel	24.13	500	0.115	1.39
Building blocks	186.03	500	0.115	10.70
Brick	275.94	500	0.115	15.87
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	5.67	500	0.115	0.33
Insulation door (multifunctional door)	2.34	500	0.115	0.13
Ceramics	66.78	500	0.115	3.84
Coating	8.55	500	0.104	0.44
Cable	0.22	500	0.334	0.04
Pipes	2.78	500	0.115	0.16
Polycarbonate	4.95	500	0.115	0.28
Sum of C_{YS}				81.74

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database.)

Appendix T. CO_2 emission amount of building materials transportation stage (C_{YS}) regarding Polycarbonate B made fixed external shading devices (50-year building lifespan)

Construction material	Total weight of material (t)	Transportation distance (km)	CO_2 emission factor ($kgCO_2e/t \cdot km$)	CO_2 emission amount (tCO_2e)
Concrete	3,461.73	40	0.115	15.92
Rebar	173.20	500	0.115	9.96
Section steel	2.14	500	0.115	0.12
Cement	85.53	500	0.115	4.92
Ready mixed mortar	378.47	40	0.115	1.74
Sand	273.70	500	0.115	15.74
Extruded polystyrene foam board	2.86	500	0.115	0.16
NEA insulation leveling gel	24.13	500	0.115	1.39
Building blocks	186.03	500	0.115	10.70
Brick	275.94	500	0.115	15.87
Insulated metal profile + 6mm medium light transmission Low-E + 12mm argon gas + 6 mm light transmission	5.67	500	0.115	0.33
Insulation door (multifunctional door)	2.34	500	0.115	0.13
Ceramics	66.78	500	0.115	3.84
Coating	8.55	500	0.104	0.44
Cable	0.22	500	0.334	0.04
Pipes	2.78	500	0.115	0.16
Polycarbonate	12.46	500	0.115	0.72
Sum of C_{YS}				82.18

*Note: 1t equals to 1,000kg.
(Source: CEEB 2024 database.)

Appendix U. CO_2 emission amount at the stage of building operation regarding Merbau A made fixed external shading devices (50-year building lifespan)

Category	Annual power consumption (E_i) (kWh/a)	Carbon emissions factor (Q_i) ($kgCO_2/kWh$)	Annual carbon emissions amount (tCO_2/a)	Lifespan (y)	Total carbon emissions amount (tCO_2)
Cooling system	78,287	0.5271	41.27	50	2,063.25
Air conditioning fan	32,027	0.5271	16.88	50	844.07
Lighting system	18,310	0.5271	9.65	50	482.56
CO_2 emission amount of power consumption (sum of C_M):					3,389.88
(-) Fixed amount of carbon sink (sum of Cp):					82.89
CO_2 emission amount at building operation stage:					3,306.99

(Source: CEEB 2024 database.)

Appendix V. CO_2 emission amount at the stage of building operation regarding Merbau B made fixed external shading devices (50-year building lifespan)

Category	Annual power consumption (kWh/a)	Carbon emissions factor ($kgCO_2/kWh$)	Annual carbon emissions amount (tCO_2/a)	Lifespan (y)	Total carbon emissions amount (tCO_2)
Cooling system	77,760	0.5271	40.99	50	2,049.37
Air conditioning fan	32,027	0.5271	16.88	50	844.07
Lighting system	18,310	0.5271	9.65	50	482.56
CO_2 emission amount of power consumption (sum of C_M):					3,376.00
(-) Fixed amount of carbon sink (sum of Cp):					82.89
CO_2 emission amount at building operation stage:					3,293.11

(Source: CEEB 2024 database.)

Appendix W. CO_2 emission amount at the stage of building operation regarding Aluminum A made fixed external shading devices (50-year building lifespan)

Category	Annual power consumption (kWh/a)	Carbon emissions factor ($kgCO_2/kWh$)	Annual carbon emissions amount (tCO_2/a)	Lifespan (y)	Total carbon emissions amount (tCO_2)
Cooling system	78,287	0.5271	41.27	50	2,063.25
Air conditioning fan	32,027	0.5271	16.88	50	844.07
Lighting system	18,310	0.5271	9.65	50	482.56
CO_2 emission amount of power consumption (sum of C_M):					3,389.88
(-) Fixed amount of carbon sink (sum of Cp):					82.89
CO_2 emission amount at building operation stage:					3,306.99

(Source: CEEB 2024 database.)

Appendix X. CO_2 emission amount at the stage of building operation regarding Aluminum B made fixed external shading devices (50-year building lifespan)

Category	Annual power consumption (kWh/a)	Carbon emissions factor ($kgCO_2/kWh$)	Annual carbon emissions amount (tCO_2/a)	Lifespan (y)	Total carbon emissions amount (tCO_2)
Cooling system	77,760	0.5271	40.99	50	2,049.37
Air conditioning fan	32,027	0.5271	16.88	50	844.07
Lighting system	18,310	0.5271	9.65	50	482.56
CO_2 emission amount of power consumption (sum of C_M):					3,376.00
(-) Fixed amount of carbon sink (sum of Cp):					82.89
CO_2 emission amount at building operation stage:					3,293.11

(Source: CEEB 2024 database.)

Appendix Y. CO_2 emission amount at the stage of building operation regarding Polycarbonate A made fixed external shading devices (50-year building lifespan)

Category	Annual power consumption (kWh/a)	Carbon emissions factor ($kgCO_2$/kWh)	Annual carbon emissions amount (tCO_2/a)	Lifespan (y)	Total carbon emissions amount (tCO_2)
Cooling system	78,287	0.5271	41.27	50	2,063.25
Air conditioning fan	32,027	0.5271	16.88	50	844.07
Lighting system	18,310	0.5271	9.65	50	482.56
CO_2 emission amount of power consumption (sum of C_M):					3,389.88
(-) Fixed amount of carbon sink (sum of Cp):					82.89
CO_2 emission amount at building operation stage:					3,306.99

(Source: CEEB 2024 database.)

Appendix Z. CO_2 emission amount at the stage of building operation regarding Polycarbonate B made fixed external shading devices (50-year building lifespan)

Category	Annual power consumption (kWh/a)	Carbon emissions factor ($kgCO_2$/kWh)	Annual carbon emissions amount (tCO_2/a)	Lifespan (y)	Total carbon emissions amount (tCO_2)
Cooling system	77,760	0.5271	40.99	50	2,049.37
Air conditioning fan	32,027	0.5271	16.88	50	844.07
Lighting system	18,310	0.5271	9.65	50	482.56
CO_2 emission amount of power consumption (sum of C_M):					3,376.00
(-) Fixed amount of carbon sink (sum of Cp):					82.89
CO_2 emission amount at building operation stage:					3,293.11

(Source: CEEB 2024 database.)