______________________Vinnytsia National Technical University________________
(Full name of the higher education institution)

_________Faculty of Construction, Civil and Environmental Engineering__________
(full name of the institute, name of the faculty)

_________Department of Construction, Urban Planning and Architecture ________
(full name of the department)

MASTER THESIS

« Multicriteria design of modern multilayered envelopes in terms of sustainability»

Assigned by: 2nd year student, group 2B-23 m

Speciality 192 Construction and Civil Engineering
(Code and name of the Speciality)

Haina XU
(First name and last name)

Supervisor: PhD, Associate Prof. Yuriy BIKS
(First name and last name)

Opponent: PhD, Prof. Ivan KOTS
(First name and last name)

____
(surname and initials)

Approved to be defended

Head of Department CEUPA

PhD, Associate Prof. Vitaliy SHVETS
(First name and last name)

«_18 »_June__________________2025

Vinnytsia, VNTU – 2025

Vinnytsia National Technical University
(Full name of the higher education institution)
Faculty of Construction, Civil and Environmental Engineering_
(Full name of the institute, name of the faculty)
Department of Construction, Urban Planning And Architecture
Education level__________________ _Second (Master's)_________
Studies direction 19___Architecture and _Construction _
(Code and name)
Speciality 192 Construction and Civil Engineering
(Code and name)
Educational Program Industrial and Civil Engineering_

APPROVED
Head of Department CEUPA
_Vitaliy SHVETS
"18"_June_____________ 2025

TASK

FOR MASTER QUALIFICATION THESIS TO STUDENT

XU Haina
(FULL NAME)

1. Master's qualification thesis topic_« Multicriteria design of modern multilayered envelopes in terms of sustainability»

Master's thesis supervisor BIKS Yuriy, Associate Prof. of the CEUPA Department,
(Surname, first name, patronymic, academic degree, academic title)

approved by order of the higher educational institution from «__»_____2025 No___

2. Deadline for submission of work by a master's student _14.06.2025.

3. Initial thesis data: Data from the open sources, research background regarding the problems of high energy consumption and high carbon emissions of buildings in the tropical climate of Hainan.

4. Content of the settlement and explanatory note (list of issues to be developed): The introduction should reflect the relevance of the topic, its purpose, scientific novelty, practical significance, research tasks, subjects, and central bodies. The research section comprises three chapters: Chapter 1, Theoretical Basis and Literature Review. Chapter 2, Technical Pathways and standards for sustainable Architectural design. Chapter 3, Case Analysis: Haikou Binhai Jingyue Residential Building. Taking Binhai Jingyue as a case, this paper analyses technologies such as elevated floors, prefabricated construction, and green roofs. Compared to ordinary residences, it saves energy by 10.79% and provides thermal comfort by 54.77%, achieving a two-star standard (71.45 points). Cost control suggestions are proposed. Chapter 4, Conclusions and Prospects, summarises the applicability of the framework in Hainan (energy conservation, emission reduction, comfort), reaching the two-star standard. Analyse the limitations (single case), look forward to AI energy consumption prediction and localised technology research and development, and guide green buildings in tropical regions.

5. List of graphic material (with exact indication of mandatory drawings): 1-3-Topic. Purpose and tasks of the work, novelty, practicality, and significance. 4-6-Bionic architectural design status; 7-11-Development and practical application of bionic building facade theory to gain new ideas; 14-Economic calculation results: 15-Conclusion

6. Consultants of Master qualification thesis parts

Part	Surname, initials and position of consultant	Signature and date	
		Task issued	Task accepted
Introduction, Chapter 1	Yuriy BIKS, Associate Prof. of the CEUPA Department		
Chapter 2	Yuriy BIKS, Associate Prof. of the CEUPA Department		
Chapter 3	Yuriy BIKS, Associate Prof. of the CEUPA Department		
Chapter 4	Yuriy BIKS, Associate Prof. of the CEUPA Department		
Economic	Olena LYALIUK, Associate Prof. of the CEUPA Department		

7. Issue date of the task 15.01.2025

CALENDAR SCHEDULE

No	The name of the stages of the master's qualification work	The term of performance of work stages	Note
1	Analysis of the sustainable design principles, the challenges and problems it faces and the current development status in China—preparation of Chapter 1.		
2	Preparation for the research objectives, tools and methodology.		
3	Chapter 2 Research methods and tools		
4	Chapter 3: Actual projects, the application of sustainable design principles is compared with traditional architecture.		
5	Chapter 4. Case study building analysis.		
6	Chapter 5 Economic analysis, social benefits and ecological benefits. Prospects and future research directions.		
7	Preparation for publication and publication of MQT results. Approbation of the work.		
8	Antiplagiarism check		
9	Preliminary defence of the Master's qualification thesis		

Master student ____________ XU Haina
(Signature) (Surname and initials)

Master's thesis supervisor ____________ BIKS Yuriy
(signature) (Surname and initials)

ABSTRACT

Xu Haina. Multicriteria design of modern multilayered envelopes in terms of sustainability, Master's qualification thesis in the speciality 192 - "Civil Engineering and Construction", Educational Project- "Industrial and Civil Engineering". VNTU, 2025. 88 p.

In English. Bibliography: 44 titles; fig. 12; tabl. 16.

Sustainable architectural design is currently one of the hottest research topics in the world. Maintaining a comfortable indoor environment while reducing energy consumption is a highly challenging task that has garnered the attention of experts worldwide. With the latest advancements in building performance simulation tools, it is now possible to predict and evaluate building performance during the design phase. A multi-standard collaborative design framework was developed based on Hainan's climate and geographical characteristics, incorporating sustainable design theory, passive low-energy technology, PKPM tools, and Tsinghua Sville software applications, among others, to reduce energy consumption and achieve a comfortable interior environment within the building. This paper compiles and reviews a large number of studies on sustainable design guidelines for buildings. Based on the statistical results, this thesis highlights the limitations of the research area and proposes some potential breakthrough directions.

The master's qualification thesis contains 17 sheets of the graphic part.

Key words: Design optimisation, Building performance simulation, building envelope, sustainable design

CONTENT

INTRODUCTION

Actuality of the theme. The construction industry is a significant source of global energy consumption and carbon emissions, accounting for about 40 per cent of total energy consumption, with HVAC systems contributing significantly. Driven by China's "dual carbon" goals (peaking carbon emissions by 2030 and achieving carbon neutrality by 2060), buildings need to balance functional requirements and resource efficiency to achieve a low-carbon transition. As an international free trade port, Hainan has a tropical Marine climate (high temperature, high humidity, strong sunlight, frequent typhoons), which puts higher demands on the energy efficiency, climate adaptability and sustainability of buildings. With the support of policies such as the "Hainan Green Building Evaluation Standard" (DBJ 46-064-2023), promoting sustainable building design has become the key to building an eco-friendly and livable island. This study focuses on the regional characteristics of Hainan and explores the application of multi-standard design in reducing energy consumption and enhancing comfort to support the green development of the region.

Through the integration of multi-standard design, the entire life cycle of buildings (preparation of materials, construction, operation, and waste disposal) will be low-carbonized.

- In Hainan's unique tropical Marine climate (high temperature, high humidity, strong sunlight, frequent typhoons), sustainable design of buildings is of even greater significance.

Connection of work with scientific programs, plans, topics.

This work was conducted within the framework of scientific research at the Department of Construction, Urban Planning and Architecture of Vinnytsia National Technical University (VNTU), Research on Multi-Standard Design for the Sustainability of Modern Architecture. It aligns with the university’s emphasis on addressing real-world engineering challenges under specialty 192 "Construction and Civil Engineering."

Purpose and tasks of the research

In response to the tropical climate of Hainan, a multi-standard sustainable design framework is constructed to achieve low-carbonization throughout the entire life cycle of buildings and enhance indoor comfort, responding to the "dual carbon" goals and Hainan's ecological civilization construction, and providing theoretical and practical support for the development of green buildings. Applying sustainable design principles to residences makes a major contribution to reducing energy consumption and enhancing indoor comfort.

The following problems must be solved:

This study aims at the problems of high energy consumption, high carbon emissions and insufficient comfort of buildings under the tropical climate (high temperature, high humidity, strong sunlight and frequent typhoons) in Hainan, and constructs a multi-standard sustainable design framework to solve the following problems:

The carbon emissions throughout the entire life cycle of buildings are high, making it difficult to achieve the "dual carbon" goals.

The tropical climate has poor adaptability and high energy consumption (accounting for 40% of the global total).

The implementation cost of the green building policy in Hainan (DBJ 46-064-2023) is high and its popularization is difficult. Through case verification (energy saving of 10.79% and carbon emission reduction of 65.82%), a low-carbon, comfortable and economical technical path is provided.

Object of the study

Energy efficiency performance of multilayered envelopes

Subject of the study

Performance optimisation of green buildings in the tropical climate of Hainan

Methods of research

This research adopts a method combining theoretical analysis, simulation verification and case study:

Literature Review: Sort out the theories of sustainable architecture and multi-standard design, and construct the design framework of tropical climate in Hainan.

Technical simulation: Use PKPM [37], BIM [40] and SEDU2022 [41] software to simulate energy consumption (saving 10.79%), carbon emissions (reducing 65.82%), thermal comfort (54.77%) and acoustic performance.

Case Analysis: Based on the verification framework of Binhai Jingyue residential Building, it reached the two-star standard (71.45 points).

Policy Evaluation: Under the DBJ 46-064-2023 standard, suggestions for promotion are put forward.

Scientific novelty of the obtained results

This study focuses on the tropical climate of Hainan and constructs a multi-standard sustainable design framework. The innovation lies in:

Novel theory: For the first time, it integrates six dimensions, including energy, materials, and space, filling the theoretical gap in the full life cycle design in Hainan.

Technological breakthrough: By integrating local materials (such as volcanic stones) and traditional wisdom (such as ventilation in Li ethnic boat houses), typhoon-resistant and low-carbon technologies have been developed (saving energy by 10.79% and reducing carbon emissions by 65.82%).

Practical verification: Through the Binhai Jingyue case (with a two-star standard and a score of 71.45), a new model for green buildings on tropical islands has been provided.

Practical significance of the obtained results

Advancing Hainan's Green Building: The Binha Jingyue case study (10.79% energy savings, 65.82% carbon emission reduction) validates the multi-criteria design framework, achieving Hainan's Green Building Two-Star Standard (score: 71.45), supporting the Hainan Green Building Evaluation Standard (DBJ 46-064-2023) and promoting adoption in smaller cities.

Supporting "Dual Carbon" Goals: Reduces building carbon emissions, contributing to China's 2030 carbon peak and 2060 carbon neutrality targets.

Enhancing Living Quality: Improves thermal comfort (54.77% ratio) and acoustics (43 dB noise), enhancing resident life in Hainan.

Economic Viability: Green buildings recover costs in 5–8 years, facilitating widespread adoption.

Global Reference: Offers sustainable design solutions for tropical islands, supporting SDG 11 (Sustainable Cities) and SDG 13 (Climate Action).

Personal contribution of the master's student

As the principal researcher, I proposed and developed a multi-standard sustainable design framework tailored to Hainan's tropical climate, integrating energy, materials, and spatial efficiency, thereby filling the theoretical gap in the region. The technical solution of the Binhai Jingyue residential building case was designed (energy saving 10.79%, carbon emission reduction 65.82%). The effect of the framework was verified through PKPM and BIM simulation, achieving a two-star standard (score: 71.45). Analyse the implementation of the green building policy in Hainan (DBJ 46-064-2023), put forward cost control suggestions, and provide new ideas for the development of green buildings in tropical islands.

Approbation of the results of the master’s thesis

1. The main results of this work were presented at the thesis [42] in the electronic version on the website of VNTU in the international scientific and practical conference Research, Problems, Prospects (MN-2025) Xu Haina. The Study on Research on Multi-Standard Design for the Sustainability of Modern Architecture/ Biks Yuriy S, Xu Haina // Abstracts of the report at the International scientific and practical Internet conference Youth in science: research, problems, prospects (MN-2025), (VNTU) – Electronic text data – 2025. URL:

https://conferences.vntu.edu.ua/index.php/mn/mn2025/paper/viewFile/25472/21053 (Last accessed 06.06.2025).

Publications [43, 44]

1. Xu Haina. Discussion on the design of housing types for affordable housing. I. Design concepts and approaches for housing types. *Housing Science*. 2012. № 7. P. 60-62. DOI: 10.3969/j.issn.1673-1093.2012.07.020.
2. Xu Haina. The optimization path of green building technology in architectural design. *Housing Science*. 2021. № 3. P.202 DOI: 10.12277/j.issn.1673-7075.2021.03.445.

CHAPTER 1 STATE OF THE ART IN THE MULTICRITERION DESIGN OF MODERN MULTILAYERED ENVELOPES

1.1 Research Background and significance

The construction industry is a major source of global energy consumption and carbon emissions, accounting for about 40 percent of total energy consumption, with HVAC systems contributing significantly. Driven by China's "dual carbon" goals (peaking carbon emissions by 2030 and achieving carbon neutrality by 2060), buildings need to balance functional requirements and resource efficiency to achieve a low-carbon transition. As an international free trade port, Hainan has a tropical Marine climate (high temperature, high humidity, strong sunlight, frequent typhoons), which puts higher demands on the energy efficiency, climate adaptability and sustainability of buildings. With the support of policies such as the "Hainan Green Building Evaluation Standard" (DBJ 46-064-2023), promoting sustainable building design has become the key to building an eco-friendly and livable island. This study focuses on the regional characteristics of Hainan and explores the application of multi-standard design in reducing energy consumption and enhancing comfort to support the green development of the region.

Through the integration of multi-standard design, the entire life cycle of buildings (preparation of materials, construction, operation, and waste disposal) will be low-carbonized.

- In Hainan's unique tropical Marine climate (high temperature, high humidity, strong sunlight, frequent typhoons), sustainable design of buildings is of even greater significance.

1.2 Research Objectives and Methods

1.2.1 Research objectives

In the context of high global building energy consumption and China's "dual carbon" goals, sustainable building design has become a key path to addressing the energy crisis and climate change. Hainan, as an international free trade port, has a unique tropical Marine climate (high temperature, high humidity, strong sunlight, frequent typhoons), which poses higher requirements for environmental adaptability and resource efficiency in building design. This study aims to build a multi-standard sustainable design framework based on the integration and optimisation of energy, materials and space efficiency, and to achieve low-carbonization throughout the entire life cycle of buildings (material preparation, construction, operation, waste disposal) and improvement of indoor environment comfort by Hainan's tropical climate characteristics. The specific research objectives include:

1. Theoretical objective: Systematically integrate sustainable architectural design theory with multi-standard design methods, extract design principles applicable to the tropical island climate, and fill the theoretical gap in Hainan's regional characteristics and complete life cycle analysis.

2. Technical objective: To develop a sustainable design technology path that ADAPTS to Hainan's high temperature, high humidity, strong sunlight and typhoon environment through passive low-energy technology, renewable energy utilization, localized materials and traditional architectural wisdom.

3. Practice objective: Use the Haikou Binhai Jingyue residential building as a case study to verify the effectiveness of the multi-standard design framework in terms of energy efficiency, carbon emission control, indoor thermal comfort and acoustic performance to reach the two-star standard of green buildings in Hainan Province.

4. Policy and Application Objectives: To provide technical support and practical models for the implementation of green building policies in Hainan, and to offer referenceable experience for sustainable architectural design in tropical island regions around the world.

By achieving these goals, this study not only responds to China's "dual carbon" strategy and Hainan's ecological civilization construction needs, but also provides theoretical and practical guidance for the sustainable development of buildings in tropical regions.

1.2.2 Research methods

To achieve the above goals, this study adopts a multi-method system that combines theoretical analysis, simulation verification and case studies, and integrates interdisciplinary tools from architecture, environmental science and engineering technology to ensure the scientific and practical nature of the study. The specific research methods are as follows:

1. Literature review and theoretical construction:

By systematically searching domestic and international academic databases (such as CNKI, Web of Science), sort out the theoretical framework and key technologies of sustainable architectural design, multi-standard design and tropical climate architecture research.

2. Based on the ecological architecture theory (Yeang, 1998), the hierarchical design method (Xia Yun et al., 2010), and the multi-criteria optimisation model (Ali & Armstrong, 2017), construct a multi-criteria design framework applicable to Hainan, covering energy efficiency, material recycling, spatial function, and climate adaptability.

3. Technical simulation and data analysis:

Use the PKPM series of software (PKPM-Energy, PKPM-CES, PKPM-TCD) to simulate building Energy consumption, carbon emissions and indoor thermal comfort performance, and quantify the energy efficiency and environmental benefits of design schemes.

Use BIM technology (based on Revit or Tianzheng software) to optimize the building's spatial layout and pipeline separation, and simulate natural lighting, ventilation and material utilization efficiency.

Use SEDU2022 software to analyze the sound insulation performance of components and the indoor noise level to ensure that the acoustic comfort meets the standards.

The insulation performance of the envelope was evaluated through the PBECA software to verify its adaptability to the high temperature, high humidity and strong sunlight environment in Hainan.

4. Case studies and empirical validation:

Select the Binhai Jingyue residential building in Qiongshan District, Haikou City as the research object, and analyze the application effects of sustainable design technologies such as the elevated floor, prefabricated construction (aluminum formwork, composite slab), green roof, and photovoltaic integration.

The actual performance of the multi-standard design framework was verified through energy consumption simulation (Annex A.1), thermal comfort evaluation (Annex A-2), thermal insulation performance analysis (Annex A.3), and acoustic performance testing (Annex A.4), and its compliance with the Hainan Green Building Evaluation Standard (DBJ 46-064-2023) was evaluated.

Conduct economic analysis to compare the cost and long-term benefits of two-star green buildings with ordinary residences and evaluate the cost-effectiveness of sustainable design.

Comprehensive evaluation and policy alignment

Based on simulation data and case analysis results, comprehensively evaluate the performance of the multi-criteria design framework in terms of energy, environment, economy and social benefits, and summarize its applicability in the tropical climate of Hainan.

Analyze the policy compliance of the design scheme in comparison with the "Hainan Green Building Evaluation Standard" and the "General Specification for Building

Energy Efficiency and Renewable Energy Utilization" (GB 55015-2021), and propose optimization suggestions.

1.2.3 Method features

This research method combines the regional characteristics of Hainan, focuses on the synergistic optimization of passive design and active technology, and emphasizes the modern application of local materials (volcanic stone, bamboo and wood) and traditional architectural wisdom (ventilation structure of Li houseboats). By using the hierarchical design method to optimize the performance of complex buildings in stages, and using BIM and PKPM tools to achieve a closed loop of design-simulation-verification, the scientific and operational nature of the research results is ensured. In addition, the case analysis focuses on actual projects in Hainan, with detailed data and strong practical guidance significance.

1.3 Thesis structure and innovation points

Paper Structure

This paper focuses on the research topic of multi-standard design for building sustainability in the context of Hainan's tropical Marine climate, systematically constructs a design framework based on the integration and optimisation of energy, materials and space efficiency, and discusses it through theoretical analysis, simulation verification and case studies. The structure of the paper is clear, and it is divided into six main parts:

Introduction: Elaborate on the background and significance of the research, analyse the importance of the construction industry in global energy consumption and carbon emissions, propose research objectives and methods in combination with China's "dual carbon" goals and the construction needs of the Hainan Free Trade Port, and clarify the application value of multi-standard design in the tropical climate of Hainan.

Theoretical basis and literature review: Systematically review the domestic and international status of sustainable architectural design theory, multi-standard design methods, and architectural research in Hainan's tropical climate, and analyze research gaps such as insufficient integration of multiple standards and lack of full life cycle analysis to provide theoretical support for the framework of this paper.

Technical pathways and standards for sustainable architectural design: Based on the multi-criteria design framework, elaborate on the specific technical strategies for passive design (such as natural ventilation and external shading), active technologies (such as photovoltaic integration), and ecosystem design in six dimensions: energy efficiency, material recycling, spatial functionality, climate adaptability, ecological protection, and social benefits, and verify the effects with PKPM and BIM simulations.

Case study: Haikou Binhai Jingyue Residential Building: Taking the 26-storey residential building in Qiongshan District, Haikou City as a case study, this study examines the application effects of sustainable design technologies such as site layout, prefabricated construction (aluminum formwork, composite slabs), green roof, photovoltaic integration, and pipeline separation. Through simulation data of energy consumption, carbon emissions, thermal comfort and acoustic performance, the practical effects and policy compliance of the multi-standard design framework are verified.

Conclusions and Prospects: Summarize the research conclusions, emphasize the applicability and superiority of the multi-standard design framework in the tropical climate of Hainan, analyse the limitations of the research (such as insufficient universality of a single case), and propose future directions such as AI energy consumption prediction, localised technology research and development, etc.

References and Appendices: Provide comprehensive literature support, including policy standards, academic papers, and monographs. The appendix contains technical analysis reports on energy consumption, carbon emissions, thermal comfort, insulation performance, and acoustic performance, with detailed data to provide a quantitative basis for the study.

Innovation points

This study is highly innovative at the theoretical, methodological, technical and practical levels, specifically in the following aspects:

Theoretical innovation: Constructing a multi-standard design framework tailored to Hainan's tropical climate

In response to Hainan's tropical Marine climate characteristics, which include high temperatures, high humidity, strong sunlight, and frequent typhoons, systematically integrate sustainable architectural design theories (such as Yeang's ecological architecture theory and hierarchical design methods) with multi-standard optimisation models to extract design principles suitable for the tropical island climate.

It fills the theoretical gap in Hainan's regional characteristics and builds life cycle analysis, and for the first time integrates the six dimensions of energy efficiency, material recycling, spatial function, climate adaptability, ecological protection and social benefits to form a design framework that combines theory and practice.

Methodological innovation: The application of interdisciplinary integrated research methods

A closed-loop research system of "design-simulation-verification" is formed by integrating literature reviews, theoretical construction, technical simulation, and case studies, and combining interdisciplinary tools from architecture, environmental science, and engineering technology.

The hierarchical design approach was adopted to optimize the performance of complex buildings in stages. Through the PKPM series of software (PKPM-Energy, PKPM-CES, PKPM-TCD) [37], BIM technology [40]and SEDU2022 software [41], Energy consumption, carbon emissions, thermal comfort and acoustic performance were quantified to ensure the scientific and operational nature of the research results.

Technology innovation: Localization and modern application of conventional wisdom

Combining Hainan's native materials (such as volcanic stone, bamboo and wood, coconut shell fiber) with traditional architectural wisdom (such as the ventilation structure of Li houseboats) to develop sustainable technological paths that adapt to high temperature, high humidity, and typhoon environments, such as natural ventilation in elevated floors, deep overhang shading, and moisture-heat resistant materials.

Integrate passive low-energy technologies (such as Low-E insulating glass, green roof), active technologies (such as building-integrated photovoltaics, variable frequency air conditioning) and ecosystem designs (such as rainwater recycling, reclaimed water reuse) to achieve 10.79% increase in energy efficiency and 65.82% reduction in carbon emissions (Annex A.1).

Practical innovation: Case validation and policy alignment

Taking the Haikou Binhai Jingyue residential building as A case study to verify the effectiveness of the multi-standard design framework in the actual project, the total project score was 71.45 points, reaching the Hainan Green Building two-star standard (DBJ 46-064-2023), with an energy-saving rate of 10.79%, A thermal comfort ratio of 54.77%, and acoustic performance meeting the standards (Annex A.1 to A.4).

Through alignment with policies such as the "Hainan Green Building Evaluation Standard" [3] and the "General Specification for Building Energy Efficiency and Renewable Energy Utilization", optimisation suggestions for cost control, technology improvement and digital management were proposed, providing a practical model for the regional promotion of green buildings in Hainan.

Regional innovation: A model of sustainable development adapted to the tropical island climate

In response to the special challenges of Hainan's tropical climate (such as typhoon resistance, moisture resistance, and intense sunlight), the design incorporates regional characteristic technologies (such as photovoltaic wind-resistant design and permeable pavement), providing a reference for sustainable architectural design in tropical island regions around the world.

Through designs such as elevated public Spaces and ecological courtyards, the community cohesion and the quality of life of residents have been enhanced, contributing to the construction of an eco-friendly and livable island in Hainan and demonstrating the social benefits of sustainable design.

Conclusions to Chapter 1

1. Defines the problem of high energy consumption and low sustainability in tropical climates, with a focus on Hainan.
2. Establishes a comprehensive, multicriteria framework that combines energy, materials, spatial layout, and comfort.
3. Integrates theoretical, simulation-based, and case-study methods.
4. Highlights scientific novelty: complete life-cycle approach, local material adaptation, and simulation-based validation.

CHAPTER 2 THEORETICAL BASIS AND LITERATURE REVIEW

Sustainable architectural design is a core research field that addresses the global energy crisis and climate change, and has become a significant topic in both architecture and environmental science. In the context of China's "dual carbon" goals and the development of the Hainan International Free Trade Port, sustainable architectural design must consider multiple dimensions, including energy efficiency, material recycling, spatial functionality, and climate adaptability. This section provides a theoretical basis for the multi-standard design framework proposed in this paper by systematically reviewing the current research status of sustainable architectural design theory and multi-standard design at home and abroad, analysing the special needs of sustainable design in the tropical climate of Hainan, identifying research gaps.

2.1 Theory of Sustainable architectural design

Sustainable architectural design aims to reduce environmental impact by optimising resource utilisation throughout the entire life cycle of a building (design, construction, operation, demolition), while enhancing the comfort and health of occupants. Yeang (1998) proposed the theory of eco-architecture in his classic work Designing with Nature, advocating that buildings should be in harmony with the natural environment and reduce energy consumption through passive design (such as natural ventilation and lighting) and the use of renewable energy. This theory offers guidance for architectural design in tropical regions, such as responding to hot and humid climates through the use of deep overhanging eaves and ventilation corridors.

In the field of passive low-energy design, Ng et al. (2019) studied climate-adaptive design for high-rise buildings in the tropics, pointing out that air conditioning energy consumption could be reduced by 90% through optimisation of building orientation, envelope insulation, and natural ventilation. In a domestic study, Song Yehao and Lin Borong (2015) suggested that passive strategies, such as external shading and green roofing, should be given priority in tropical regions to reduce the heat island effect and cooling demand. These studies offer theoretical support for architectural design in Hainan; however, they are primarily focused on a single technology and lack a systematic integration of multi-standard design.

The Hierarchical Design Method is another important theory of sustainable architectural design. Xia Yun et al. (2010) proposed the performance optimisation of complex building structures through four steps: target analysis, inventory formulation, effect prediction, and scheme optimization. This method is particularly applicable in the design of prefabricated buildings in Hainan, as it enables the simulation of energy consumption and carbon emissions through BIM technology, thereby optimising the design scheme. However, existing research has rarely explored the specific application of the hierarchical approach in tropical island climates, particularly in terms of adaptability in typhoon resistance and moisture-proof design.

2.2 Multi-standard design connotations and methods

Multi-Criteria Design (MCD) is a design approach that considers multiple performance indicators, including energy efficiency, material recycling, spatial functionality, economic viability, and social benefits. In an international study, Ali and Armstrong (2017) suggested, by comparing global cases of sustainable design for high-rise buildings, that MCD needs to balance short-term costs with long-term benefits, especially by prioritising climate adaptability and energy efficiency in tropical regions. They emphasised the use of life cycle assessment (LCA) to quantify building carbon footprint and provide data support for multi-standard optimisation.

In China, Wang Jianguo and Xu Lei (2020) proposed a multi-objective sustainability optimisation framework for high-rise buildings based on Building Information Modelling (BIM) technology, which combines energy consumption, cost, and comfort indicators, and optimises design schemes through genetic algorithms. Li Baofeng and Zhang Tong (2018), in response to the high temperature and humidity environment in Hainan, suggested that multi-standard design should incorporate local materials (such as volcanic stone, bamboo and wood) and traditional architectural wisdom (such as the ventilation structure of the Li boat house) to reduce transportation carbon emissions and enhance cultural identity. These studies provide methodological inspiration for the multi-standard framework of this paper, but lack a systematic integration of Hainan's green building policies, such as the two-star standard.

2.3 Research on Sustainable Design in Hainan's tropical climate

Hainan's tropical Marine climate (high temperature, high humidity, intense sunlight, frequent typhoons) poses unique challenges to architectural design. Research at home and abroad suggests that sustainable design in tropical regions should prioritise addressing issues such as heat and humidity regulation, typhoon resistance, and rainwater management. The UNEP (2022) State of the Global Building and Construction Industry Report highlights that buildings in tropical regions account for more than 30 per cent of the world's total building energy consumption, underscoring the urgent need to reduce reliance on traditional energy sources through renewable energy and passive technologies.

In a domestic study, Li Ming et al. (2022) analysed the application potential of passive energy-saving technologies (such as Low-E glass and external shading) in tropical coastal cities, taking Haikou as an example. They pointed out that natural ventilation could reduce air conditioning usage time by 30%-50%. Wang Jing (2021) explored the climate adaptability of traditional Hainan dwellings, such as arcades, and suggested that modern buildings could draw on their ventilation corridors and deep overhanging eaves for inspiration. These studies offer a localised perspective on sustainable design in Hainan, but pay less attention to life-cycle carbon emissions analysis.

In terms of renewable energy utilisation, the Chinese Renewable Energy Society (2023) evaluated the potential of building-integrated photovoltaics (BIPV) in Hainan, noting that Hainan has an average annual solar radiation of 1,635 kWh/m^2, which is suitable for rooftop photovoltaics and photovoltaic curtain walls. However, existing studies have not fully explored the wind-resistant design and long-term maintenance of photovoltaic systems in areas prone to typhoons. In addition, Hainan's green building policies (such as the "Hainan Green Building Evaluation Standard" DBJ 46-064-2023) require new buildings to be mandatorily fitted with solar systems. However, few studies have analysed the economic and technical feasibility of policy implementation.

2.4 Analysis of the current situation of the implementation of green building policies in Hainan

Hainan's green building policy, centred on the "Hainan Green Building Evaluation Standard" (DBJ 46-044-2023), came into effect on October 1, 2023. It aims to promote the green performance evaluation of civil buildings throughout their entire life cycle, covering five dimensions: safety and durability, health and comfort, convenience of life, resource conservation, and environmental livability. The standard is adapted to local conditions, highlighting Hainan's tropical climate characteristics. It requires new buildings to install solar systems, optimise ventilation and shading designs, and improve typhoon resistance and moisture resistance. The standard assesses the green rating of buildings through control items and scoring items (out of 1000 points, with a two-star rating of 650 points or more), providing a quantitative basis for policy implementation.

Implementation status: By 2025, the proportion of green buildings in new civil buildings in Hainan will increase significantly. In places like Haikou and Sanya, the proportion of projects rated at two stars or above will exceed 30%, and the proportion of prefabricated buildings will reach over 60%, in line with the goals set out in the Hainan Province Prefabricated Building Development Plan (2020-2030). DBJ 46-064-2023 has promoted the widespread application of building-integrated photovoltaics (BIPV), green roofing, and rainwater recycling systems. For instance, several projects in Haikou's Jiangdong New Area have achieved energy savings of over 50 per cent through the use of BIM technology and local materials, such as volcanic stone. The policy also promotes market acceptance by reducing initial costs through subsidies (30-50 yuan per square meter) and green finance incentives (such as low-interest loans).

Challenges and opportunities: High initial costs, a shortage of technical talent, and unbalanced regional development are present during implementation. The penetration rate of green buildings in small and medium-sized cities (such as Danzhou) is relatively low, and the implementation of policies relies on local finance and technical support. Frequent typhoons have heightened the requirements for wind resistance design of photovoltaic systems and external shading components, and technical standards need to be further optimised. In the future, in combination with the "Technical Standards for Green Building Construction in Hainan Province" (DBJ 46-072-2024, implemented in January 2025), the policy implementation effect can be enhanced through digital management (such as intelligent energy consumption monitoring) and localised technology research and development (such as moisture-heat resistant materials), providing support for Hainan's ecological civilisation construction and the development of the free trade port.

In Table 2.1, a summary of the current implementation status and key impacts of DBJ 46-064-2023 is provided.

Table 2.1 – DBJ 46-064-2023 Implementation Status summary

Aspects	Status Quo	Effectiveness	Challenges	Future Directions
Policy implementation	It will be implemented from October 2023, covering new civil buildings	More than 30 per cent are two-star projects, and 60 per cent are prefabricated buildings	The penetration rate is low, and the implementation is uneven in small and medium-sized cities	Strengthen publicity and training, and improve supporting policies
Application of Technology	Promote BIPV, green roofing, and rainwater recycling	The energy-saving rate exceeds 50%, and carbon emissions are reduced by over 65%	Inadequate typhoon resistance design and shortage of technical personnel	Develop moisture-heat resistant materials and promote intelligent monitoring
Economic incentives	Subsidies of 30-50 yuan per square meter are provided, along with green financial support	5-8 years of cost recovery and increased market acceptance	High initial cost limits promotion	Expand green finance coverage and lower loan thresholds
Social impact	Enhance residents' comfort and contribute to ecological livability	Improved health environment and enhanced community cohesion	Underawareness of the public	Strengthen the promotion of green buildings and integrate them into cultural education.

2.5 Research gaps and Positioning in this paper

The following research gaps can be identified through the above review:

Insufficient system integration of multi-standard design: Existing research mainly focuses on a single dimension (such as energy efficiency or material selection), lacking a multi-standard framework that systematically integrates energy, materials, space, climate adaptability and social benefits, especially in the application under the tropical climate of Hainan.

Insufficient in-depth exploration of Hainan's regional characteristics: While some studies have mentioned local materials and traditional architectural wisdom, they have not systematically analysed their feasibility and economic benefits in modern high-rise buildings.

Lack of complete life cycle analysis: Existing studies rarely assess the carbon footprint and long-term performance of green buildings in Hainan from the perspective of the entire life cycle of buildings (preparation of materials, construction, operation, demolition).

Lack of alignment between policy and practice: Hainan's green building policy provides norms for sustainable design, but studies have rarely explored the technical challenges and cost-effectiveness of policy implementation.

Based on the above gap, this paper presents a multi-criteria sustainable design framework for Hainan's tropical climate, integrating passive low-energy technologies, renewable energy utilisation, localised materials, and traditional building wisdom, and simulating energy consumption, carbon emissions, and comfort through PKPM and BIM technologies. The study takes the Haikou Binhai Jingyue residential building as a case study to verify the effectiveness of the framework in terms of energy efficiency, material recycling and climate adaptability, aiming to provide theoretical and practical support for the development of green buildings in Hainan, as well as references for sustainable design in tropical island regions around the world.

2.6 Literature Review summary

Table 2.2 summarises the key studies on sustainable architectural design and multi-criteria design, presenting their themes, methods, and limitations, providing a basis for the orientation of this study.

Table 2.2 – Review of key studies on sustainable architectural design and multi-criteria design

Author/Year	Subject	Methods	Main Conclusions	Limitations
Yeang (1998)	Ecological architectural design	Theoretical analysis	Buildings should coordinate with nature through passive design to reduce energy consumption.	There is a lack of specific application cases in tropical regions.
Ng et al. (2019)	Climate adaptability of tropical high-rise buildings	Simulations and case studies	Passive design can reduce air conditioning energy consumption by 90%.	No multi-standard integration and economic analysis involved.
Song et al. (2015)	Green Building strategies in Tropical regions	Theory and Design practice	External shading and green roofing reduce heat island effect.	Lack of life-cycle carbon emissions assessment.
Ali & Armstrong (2017)	High-rise building sustainability	Comparative Case studies	Multi-criteria design needs to balance costs with long-term benefits.	The tropical island climate was not focused on.
Wang et al. (2020)	Bim-based multi-objective optimization	Algorithm simulation	BIM optimizes energy consumption, cost, and comfort.	Hainan policy compliance was not explored.
Li Ming et al. (2022)	Building Energy conservation strategies in Haikou	Energy consumption simulation	Natural ventilation reduces air conditioning time by 30% to 50%.	Typhoon resistance design not analyzed.
Wang Jing (2021)	Adaptability of Traditional Dwellings in Hainan	Historical Analysis	Arcade ventilation designs can be used in modern architecture.	Lack of modern technology integration solutions.

Chinese Renewable Energy Society (2023)	Hainan BIPV Potential	Data analysis	Hainan's solar resources are suitable for photovoltaic buildings.	Wind-resistant design in typhoon conditions was not discussed.

Conclusions to Chapter 2

1. Reviews global and Chinese approaches to sustainable building, passive design, and LCA.

2. Identifies a lack of integrated multicriteria frameworks for tropical climates.

3. Highlights the underuse of traditional architectural wisdom and localised solutions.

4. Concludes with the research gap: weak integration of local policy, LCA, and adaptive methods.

CHAPTER 3 TECHNICAL PATHWAYS AND STANDARDS FOR SUSTAINABLE ARCHITECTURAL DESIGN

In the context of Hainan's tropical Marine climate (high temperature, high humidity, strong sunlight, frequent typhoons), sustainable architectural design needs to integrate multi-dimensional technical approaches to achieve low-carbonization throughout the entire life cycle and optimization of the indoor environment. Based on the multi-standard design framework, this section systematically expounds the technical strategies for energy efficiency, spatial function, climate adaptability, material recycling, ecological protection and social benefits around the two major themes of passive design and active technology and ecosystem. Passive design (3.1-3.3) reduces energy consumption through natural ventilation, shading and scientific layout, while active technology and ecosystem (3.4-3.6) enhances environmental and social benefits through renewable energy, circular materials and eco-design. The technical pathways were verified through simulations using PKPM, BIM and SEDU software, and the data are detailed in Annexes A.1 to A.4.

3.1 Passive Design Strategy

3.1.1 Energy efficiency optimization

Passive energy efficiency optimization reduces building energy consumption by reducing reliance on mechanical systems, adapting to Hainan's hot and humid climate.

Core technologies include:

Natural ventilation: Reduce air conditioning usage time by 30%-50% through ventilation corridors and elevated floor designs (such as the Li houseboat structure) (Li Ming et al., 2022).

External shading: Use aluminium louver grilles and deep overhangs to reduce radiative heat gain (Annex A.3: Roof temperature 26.57 ° C, below the limit).

Efficient enclosure: Using Low-E insulating glass and thermal insulation walls, with an energy saving rate of 10.79% (Annex A.1). PKPM-Energy simulations show that passive design can significantly reduce the cooling requirements of buildings in Hainan.

3.1.2 Passive spatial layout and functional integration

Spatial layout optimization enhances the efficiency of natural lighting and ventilation through scientific design and reduces structural redundancy. The technical pathways include:

Scientific spacing and orientation: Optimize building spacing to ensure that the main functional rooms receive adequate lighting (Section 4.2.1: North-South through).

Modular design: Using BIM technology to simulate space utilization, reduce material waste by 10%-15% [16].

Low environmental impact development: Adopting the "sponge city" concept to reduce hardened ground and protect natural water systems. Tianzheng software's [39] sunlight analysis verified the layout's adaptability to the strong sunlight environment in Hainan.

3.1.3 Passive climate-adaptive design

Climate-adaptive design responds to the challenges of high temperature, high humidity and typhoons in Hainan through building forms and components. Key technologies include:

Typhoon resistance design: Prefabricated construction and raising the ground floor to enhance wind resistance (Section 4.2.1: Elevated floor).

Thermal and humidity control: Pitched roofs, moisture-proof coatings, and breathable materials reduce condensation and mould (Annexe A.3: Exterior wall temperature 27.10-27.44 ° C).

Traditional wisdom borrowed: such as the ventilation structure of Li houseboats, combined with courtyards and vegetation to regulate the microclimate. The PKPM-TCD simulation shows that the proportion of natural ventilation thermal comfort time is 54.77% (Annexe A.2).

3.2 Active Technologies and Ecosystems

3.2.1 Renewable energy utilisation

Proactive technologies enhance energy efficiency through renewable energy and efficient systems. Core technologies include:

Solar utilization: Rooftop photovoltaics and BIPV, generating 39,240 kWh per year, accounting for 17.29 per cent of energy consumption (Annex A.1).

High-efficiency electromechanical systems: Inverter air conditioning and smart lighting reduce operating energy consumption by 20%-30% (Section 4.3).

Digital management: BIM collaborative design optimizes pipeline separation and reduces maintenance costs (4.2.7). PKPM-CES analysis confirmed that the active technology significantly reduced carbon emission intensity to 5.49 $kgCO_2/m^2 \cdot a$ (Annex A.1).

3.2.2 Material recycling and eco-protection

Material recycling and ecological protection reduce environmental impact through low-carbon materials and ecosystem design. Technical pathways include:

Native materials: Volcanic rock, bamboo wood, and coconut shell fiber to reduce transportation carbon emissions (Section 3.2).

Prefabricated buildings: Aluminum formwork turnover 300 times, composite slabs reduce construction waste by 50% (4.2.2).

Rainwater management: Roof water collection and permeable paving, reducing municipal water pressure (Section 3.5). SEDU software verified the ecological benefits of high sound insulation materials (Annex A.4: Sound insulation 47 dB).

3.2.3 Ecosystem and Social benefits

Ecosystem and social benefits enhance livability and health through green design. Key technologies include:

Reclaimed water reuse: Grey water treatment for landscape replenishment saves 30 percent of water (3.5 sections).

Healthy environment: Eco-friendly materials and optimized ventilation and lighting, PPD value 5.03%-12.28% (Annex A.2).

Community cohesion: Elevated floors serve as public Spaces to facilitate social interaction (Section 4.2.1). The data show that ecological and social benefits significantly enhance the living experience in high-density residential areas in Hainan.

3.3 Multi-standard design integration framework

Section 3 presents the technical pathways for sustainable architectural design in Hainan's tropical climate from six dimensions: energy efficiency, material recycling, spatial functionality, climate adaptability, ecological protection, and social benefits. These dimensions, through the synergy of passive low-energy technology, renewable energy utilization, localized materials, traditional architectural wisdom and ecosystem design, construct a multi-standard design framework to achieve low-carbonization throughout the building life cycle and improvement of indoor environment comfort. To visually demonstrate the integration mechanism of the dimensions. Figure 3.1 presents the core technologies and synergies of the six dimensions in the form of a technology path integration framework. Energy efficiency and climate adaptation reduce energy consumption through passive design (such as natural ventilation and shading); Material recycling and spatial functionality optimize resource utilization through prefabricated technologies such as aluminum formwork and composite panels; Ecological protection and social benefits enhance livability through rainwater recycling and healthy environment design. The framework incorporates Hainan's regional characteristics of typhoon resistance, moisture resistance and local materials (such as volcanic stone), supports the implementation of the Hainan Green Building Evaluation Standard (DBJ 46-064-2023), and provides technical guidance for sustainable building design in the tropical island region.

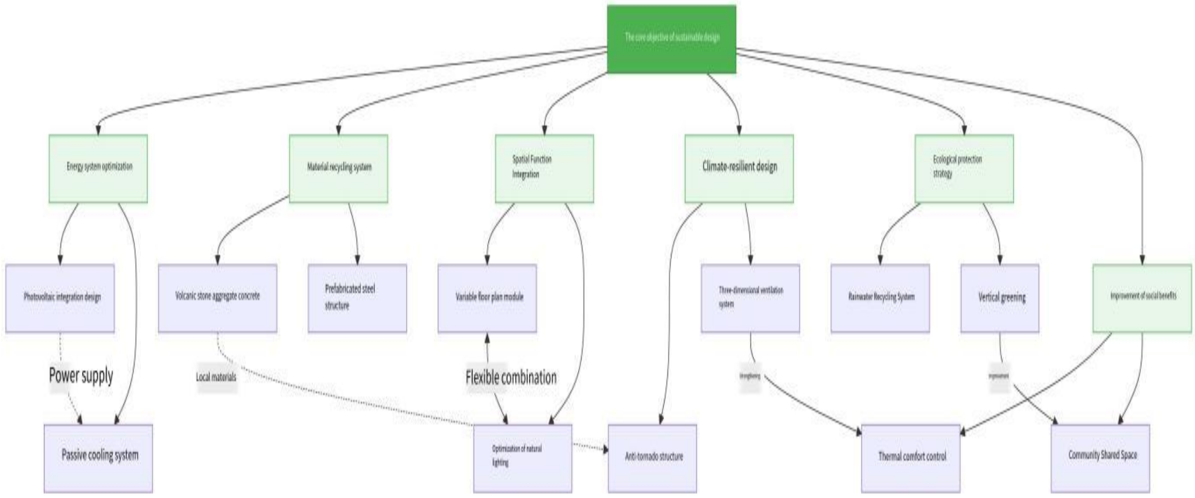

Figure 3.1 – Integrated framework of the technical path

Table 3.1 – Overview of the classification of technical paths

Sub-themes	Subsections	Core technology	Main Objectives	Data support
Passive Design	3.1 Energy Efficiency Optimization	Natural ventilation, external shading, Low-E glass	Reduce cooling energy consumption	Energy saving rate 10.79% (Annex A.1)
	3.2 Spatial layout and functional integration	Scientific spacing, modular design	Improve lighting and ventilation efficiency	Meeting lighting standards (Section 4.2.1)

Sub-themes	Subsections	Core technology	Main Objectives	Data support
	3.3 Climate-adaptive design	Typhoon resistance, heat and humidity control	Adapt to high temperatures, high humidity and typhoons	Thermal comfort 54.77% (Annex A-2)
Active technologies and ecosystems	3.4 Renewable Energy and Technology	Photovoltaic and inverter air conditioners	Improving energy efficiency	Photovoltaics accounted for 17.29% of energy consumption (Annex A.1)
	3.5 Material recycling and eco-protection	Native materials, rainwater recycling	Reducing environmental impact	Sound insulation 47 dB (Annex A.4)
	3.6 Ecosystem and Social benefits	Reclaimed water reuse, a healthy environment	Improve livability	PPD 5.03%-12.28% (Annex A-2)

Conclusion to Chapter 3

1. Proposes a six-dimensional strategy: energy, materials, space, climate, ecology, society.

2. Details passive and active technologies validated through PKPM/BIM simulations.

3. Demonstrates energy savings (10.79%), thermal comfort (54.77%), and acoustic benefits.

4. Presents a framework (Fig. 3.1) mapping synergy between sustainable design goals

CHAPTER 4 CASE STUDY: HAIKOU BINHAI JINGYUE RESIDENTIAL BUILDING

4.1 Project Overview and Site Layout

Regional location: The project is located on Longkun 1st Cross Road, east of Longkun South Road, Qiongshan District, Haikou City, Hainan Province. The sustainable design theories and principles applied in this project are as follows.

4.1.1 Site layout and Architecture

1) Orientation:

The project is a 26-storey residential building surrounded by residential areas. To ensure good lighting and orientation for the building, we planned the layout of the building by adjusting its orientation (corresponding to the prevailing direction) to achieve natural ventilation, reduce energy consumption and improve the comfort of the interior. As illustrated in the general layout plan presented in Figure 4-1, the building orientation for this project is 27.18 degrees west of south.

Figure 4.1 – Schematic of the master plan

4.2 Application of sustainable design techniques

4.2.1 Respect local culture and preserve the wisdom of traditional architecture

The ground floor is elevated(As shown in Figure 4.2, Figure 4.3): such as the ventilation structure of the Li houseboats in Hainan. Integrate the limited space environment into the natural landscape, intersperse outdoor ecological courtyards, or blur the boundaries between the building and nature, or create indoor green plant Spaces. Take humanisation as the core, fully respect the physical, mental and spiritual needs of the users, and advocate lighting, ventilation and views between people and nature.

Figure 4.2 – Photos of the elevated floor

Figure 4.3 – Photos of the elevated floor

Features of the mezzanine:

(1) Improved ventilation and microclimate

Promote natural ventilation: The elevated floor allows for free air flow, reducing the building's reliance on mechanical ventilation and lowering energy consumption.

Regulating the microclimate: The elevated floor can form a buffer zone for shading and ventilation, lowering ground temperature and improving the microclimate around the building.

(2) Flood and moisture prevention

Dealing with floods: In areas prone to waterlogging, elevated designs can prevent floods from directly entering the interior of buildings, enhancing their disaster resistance.

Moisture-proof and damp-proof: The elevated floor reduces the impact of ground moisture on the building and is particularly suitable for humid climates.

(3) Increase public space

Multi-functional use: The elevated floor can serve as a public activity space, such as a leisure area, parking lot, market, or community activity venue.

Promoting social interaction: Open elevated floors provide a place for residents to communicate and engage in activities, enhancing community cohesion.

(4) Optimize land use

Improve space utilization: Elevated floors can be used for parking, storage, or other functions to free up ground space.

Flexible layout: The elevated design provides a flexible way to use the ground floor of the building to accommodate different functional requirements.

(5) Enhance the landscape and visual effects

Visual transparency: The elevated floor makes the building appear light and reduces the sense of oppression on the surrounding environment.

Landscape integration: The elevated floor can better integrate the building with the surrounding landscape, creating an open and natural visual effect.

(6) Enhance safety

Disaster prevention and evacuation: Elevated floors can serve as emergency shelters, providing safe evacuation Spaces.

Reduce safety hazards: The elevated design reduces the enclosed space on the ground floor and lowers safety hazards (such as criminal activities).

(7) Adapt to the terrain

Mountain architecture: In sloping or uneven terrain, elevated designs can reduce earthwork and adapt to terrain changes.

Protecting the ecological environment: The elevated floor reduces the direct occupation of the ground and protects the original vegetation and ecosystem.

(8) Energy conservation and sustainability

Reduce the heat island effect: The elevated floor can reduce the building's heat radiation to the ground, alleviating the urban heat island effect.

Natural lighting: The elevated floor allows light to pass through, reducing reliance on artificial lighting.

Rainwater management: The elevated design can be combined with rainwater collection systems to improve water resource utilization efficiency.

(9) Enhance the architectural image

Modernity and uniqueness: The elevated design makes the building more modern and distinctive, enhancing its image and recognition.

Culture and regional characteristics: In some areas, the elevated design is a continuation of the traditional architectural style and reflects the regional cultural characteristics.

4.2.2 Prefabricated construction technology

The building is constructed using prefabricated methods: reusable aluminum formwork is used for the exterior walls, prefabricated walls are used for the interior walls, and composite slabs are used for the floor slabs.

Exterior material pouring formwork: aluminium formwork(As shown in Figure 4-4)

Figure 4.4 – Aluminium formwork

1. Aluminium formwork as the main pouring formwork for concrete: Aluminium formwork can be reused, achieving the sustainability of building materials.

Core features of aluminium formwork:

(1) Lightweight and high strength

Light weight: With a density of only 1/3 of that of steel formwork (about 25-30kg/㎡), it is convenient for manual handling and reduces the load on tower cranes.

High strength: Tensile strength ≥160MPa, capable of withstanding a concrete lateral pressure of over 60kN/㎡, suitable for exterior wall pouring of high-rise buildings.

(2) Precision and forming quality

Error control: Veneer processing accuracy ±0.5mm, verticality deviation ≤3mm/2m after overall assembly, achieving no plastering (saving 20-30 yuan /㎡).

Surface effect: After the concrete is formed, it can achieve a clear water effect (flatness ≤2mm/2m), reducing the need for later repair.

(3) Construction efficiency

Quick-disassembly system: Formwork can be removed within 24 hours (at temperatures ≥20 ° C), turnover speed is three times faster than wooden formwork, standard layer construction period can be compressed to 4-5 days per layer.

Easy to assemble: With pins and wedges for connection, skilled workers can assemble with an efficiency of 30-50㎡ per person per day.

(4) Economy

Turnover rate: up to 300 times or more (wooden formwork only 6-8 times), and the long-term cost is lower than that of wooden formwork (case: a 30-story project saves 15% of the overall cost).

High residual value: Aluminium can be recycled after scrapping, with a residual value rate of about 30%-40%.

(5) Green construction

Zero wood consumption: Replacing traditional wooden formwork can save 500-800m³ of wood per project (equivalent to protecting 1.5 hectares of forest).

No construction waste: No need for cutting, reduced on-site waste.

2. Special advantages of aluminium formwork in exterior wall construction

Complex node adaptability:

Customizable irregular-shaped templates (such as bay Windows, decorative lines) enable the exterior wall form in one go.

Wind pressure resistance design

Aluminum alloy frame + reinforced rib structure, better stability than wooden formwork, suitable for high-rise construction in typhoon areas of Hainan.

Heat conduction control:

Aluminum formwork has a high thermal conductivity (237W/(m·K)), so it is necessary to avoid pouring during high-temperature periods in summer and use insulation cotton to regulate the curing temperature of the concrete in winter. Limitations and countermeasures - see Table 4.1

Table 4.1 – Limitations of Aluminium Formwork and Countermeasures

Problems	Reasons	Solutions
High initial investment	The purchase price of aluminium formwork is about 1,200-1,500 yuan per square meter	It is suitable for projects with 20 or more floors and spreads out costs through high turnover.
Design change difficulties	Holes/dimensions need to be pre-cured	Use BIM for full professional collaboration and reserve casing points.
Too fast heat conduction	High temperatures cause concrete to set prematurely	Spraying retarders in high-temperature weather or conducting night construction.

4. Suitability suggestions for Hainan project

Recommended scenarios:

Residences/apartments over 20 floors (such as a super high-rise project in Haikou Jiangdong New Area, aluminum formwork saves 45 days of construction time).

Highly standardized prefabricated buildings (such as composite slab + aluminum formwork system).

Use with caution:

Low-rise buildings (< 10 floors) or irregular curved exterior walls (low cost-effectiveness ratio).

Construction techniques need to be adjusted during extreme heat periods (daytime temperature > 35 ° C).

5. Comparison of aluminum formwork vs wood formwork vs steel formwork ： Refer to Table 4.2 for details.

Table 4.2 – Aluminum formwork and wooden formwork comparison table

Parameters	Aluminum mold	Wooden formwork	Steel mold
Cost per unit	Medium (high amortization)	low	high
Turnover rate	300+ times	6-8 times	100-150 times
Molding quality	★★★★★	★★☆☆☆	★★★★☆
Environmental friendliness	Zero wood consumption	Wood dependence	Recyclable but energy-consuming

6. Conclusions

Aluminum formwork, with its advantages of high precision, fast turnover, low carbon and environmental friendliness, has become the preferred option for pouring exterior walls of high-rise buildings in Hainan, especially for projects with high standardization and tight schedules. It is necessary to combine BIM deepening design and climate-adaptive construction measures to maximize its economic benefits.

Use prefabricated membrane shell walls for the interior walls(As shown in Figure 4.5)

The membrane shell wall is a new type of building wall system formed by the combination of lightweight and high-strength membrane shell materials and prefabricated technology. It has the characteristics of quick construction, environmental protection, energy conservation and flexible design, and is widely used in modern buildings.

Figure 4.5 – Prefabricated membrane shell wall

The main advantages of using prefabricated membrane shell walls:

(1) The construction is fast and efficient

Factory prefabrication: The membrane shell wall is prefabricated in the factory and only needs to be assembled on site, significantly shortening the construction period.

Reduce on-site work: Reduce on-site wet work and reliance on manual labor, and improve construction efficiency.

All-weather construction: Less affected by weather conditions and able to work in a variety of climates.

(2) Lightweight and high strength

Lightweight: The membrane shell wall uses lightweight materials (such as composite materials, fiberglass reinforced plastic, etc.) to reduce the building load.

High strength: The material has high compressive, tensile and impact resistance, meeting the requirements of the building structure.

(3) Energy-saving and environmentally friendly

Thermal insulation: Membrane shell walls usually have good thermal insulation performance, reducing building energy consumption.

Reduce material waste: Factory prefabrication with high precision reduces material waste in line with the green building concept.

Recyclable: Some membrane shell materials can be recycled and reused, reducing construction waste.

(4) Flexible and diverse designs

Diverse shapes: Membrane shell walls can be customized in various shapes and textures according to design requirements to meet personalized design needs.

Rich in color: The surface can be treated in a variety of colors and patterns to enhance the aesthetic appeal of the building.

Strong adaptability: Suitable for a variety of building types, such as residential, commercial, public facilities, etc.

(5) Waterproof and moisture-proof

Good sealing performance: Membrane shell walls have excellent waterproof performance and are suitable for humid environments.

Moisture-proof and mold-proof: The material itself is moisture-proof and mold-proof, extending the lifespan of the wall.

(6) Sound insulation and noise reduction

Sound insulation performance: Membrane shell walls usually have good sound insulation effect, improving indoor comfort.

Reduce noise pollution: Suitable for noise-sensitive buildings such as schools, hospitals, etc.

In this project, high sound insulation materials are used for the exterior walls and household floor slabs. The sound insulation of the bedroom wall is 47 dB, which meets the high requirements, as detailed in Appendix A.4 "Report on Sound Insulation Performance of Components". Please refer to Annex A.3, "Indoor Noise Level Report", which confirms that the daytime noise level of the most unfavorable room is 43 dB, meeting the lower limit standard.

(7) Excellent seismic performance

Flexible material: The membrane shell wall material has a certain degree of flexibility and can absorb seismic energy.

Reliable connection: The prefabricated connection method is optimized to improve the overall seismic performance.

(8) Low maintenance costs

Strong durability: The membrane shell wall material is resistant to corrosion and aging and has a long service life.

Easy to clean and maintain: Smooth surface, not prone to dust accumulation, easy to clean and maintain.

(9) Economy

Lower construction costs: Shorten the construction period, reduce labor and material waste, and lower the overall cost.

Reduce later costs: Energy efficiency and low maintenance costs reduce the long-term operating costs of the building.

(10) Sustainability

Green materials: Use environmentally friendly materials to reduce pollution to the environment.

Low carbon emissions: Factory prefabrication and on-site assembly reduce carbon emissions during construction.

Resource conservation: Reduce reliance on traditional building materials such as cement and bricks, and save resources.

Summary

Prefabricated membrane shell walls have multiple advantages such as quick construction, light weight and high strength, energy conservation and environmental protection, flexible design, water and moisture resistance, sound insulation and noise reduction, superior seismic performance, low maintenance cost, economy and sustainability. It is a new type of wall system that meets the needs of modern buildings, which can significantly improve the quality, efficiency and aesthetics of buildings, while conforming to the concepts of green buildings and sustainable development.

Analysis of the advantages and disadvantages of composite slabs

A Composite Slab(As shown in Figure 4.6） is a floor/wall slab system composed of a prefabricated concrete base plate and a cast-in-place concrete layer, combining the advantages of both prefabrication and cast-in-place. The following are the core advantages and disadvantages as well as the applicable scenarios:

Figure 4.6 – Composite plate

I. Advantages

1. Efficient construction

- Prefabricated base plates are factory-produced, and after on-site installation, only thin layers of concrete need to be poured, shortening the construction period by 30% to 50% compared to full cast-in-place.

- Reduce on-site formwork support and lower labor costs.

2. Quality is controllable

- Prefabricated parts are factory-standardized production with high dimensional accuracy, avoiding problems such as honeycomb and pitted surface that are common in cast-in-place.

- The cast-in-place layer ensures integrity and reduces the risk of cracking.

3. Excellent structural performance

- As a permanent formwork, the prefabricated base plate shares the force with the cast-in-place layer, and the overall stiffness is superior to that of pure prefabricated slabs.

Its seismic performance is close to that of fully cast-in-place structures, meeting the requirements of high-rise buildings.

4 Save materials

- Prefabricated base plates can replace formwork and reduce the use of wood or steel formwork.

- The thickness of the cast-in-place layer can be optimized (typically 60-100mm) to reduce the amount of concrete used.

5. Strong applicability

- Can flexibly adapt to complex designs such as irregular floor slabs (e.g., openings, overhangs), large spans (in combination with prestressed technology), etc.

6. Green and environmentally friendly

- Reduce wet work on site and cut construction waste by more than 50%.

2. Disadvantages

1. The initial cost is high

- Prefabricated slabs require factory production and transportation, and the overall cost is 10% to 20% higher than that of full cast-in-place slabs (costs can be reduced when scaled up).

2. Complex node processing

- The reinforcement connections between prefabricated and cast-in-place layers (such as truss bars, shear keys) need to be finely constructed, otherwise they can become weak links.

- High waterproofing is required at the joints, and improper construction may lead to leakage.

3 Transport and hoisting restrictions

- Large prefabricated slabs need to be transported by dedicated vehicles, and the construction site requires the cooperation of tower cranes, which has high requirements for the site.

4. The design relies on BIM

- The precast slab division and pipeline embedding positions need to be precisely designed in advance and are difficult to change later.

5. Fire resistance needs to be verified

- Some composite slabs (such as steel truss composite slabs) require additional fireproof coating to meet the fire resistance limit requirements.

3. Applicable scenarios

1. Recommended for use

- Floor and wall slabs for prefabricated buildings (residences, office buildings, schools, etc.).

- Floor systems for large-span Spaces (such as shopping malls, factories).

- Projects with tight schedules or high environmental requirements.

2. Use with caution

- Super high-rise building core tubes and other parts with extremely high requirements for integrity (combined with cast-in-place).

- Structures with extremely irregular shapes or special loads (requiring customized design). Table 4.4 Comparison with traditional floor slabs (see Table 4.3).

Table 4.3 – Comparison table of traditional floor slabs and composite slabs

Comparison items	Laminated plates	Full cast-in-place floor slabs	Pure prefabricated floor slabs
Construction speed	Fast (reduce formwork support)	slow	Fastest (but with post-poured tape)
Integrity	Superior (cast-in-place layer reinforcement)	Optimal	Poor (dependent on node connections)
Cost	Medium to high	low	middle
Applicable Span	Medium span (6-12 m)	Flexibility	Small span (≤6 meters)
Environmental friendliness	optimal	Bad (a lot of garbage)	good

Summary

Composite slabs are the preferred solution for balancing efficiency, quality and cost, especially for prefabricated building and green construction projects. But its successful application depends on fine design, construction coordination and BIM technical support. Special attention should be paid to the moisture-proof treatment of seams in high humidity areas such as Hainan.

4.2.3 Insulation measures for enclosure structures

1. Low-E insulating glass with good heat insulation performance was selected to reduce heat loss during the exchange between the interior and exterior. Compared with traditional glass, this glass has a lower thermal emissivity, which can effectively reduce the heat loss exchanged between indoor and outdoor, achieving energy-saving effects. For low-dimensional areas like the horizon, a low transmittance of visible light can be chosen to meet the requirements. The maximum temperature on the inner surface of the roof is 26.57 ° C, which is below the limit of 28.50 ° C and meets the requirements of the Code for Thermal Design of Civil Buildings, as shown in Annex 5 of the "Calculation Report on Thermal Insulation Performance of Envelope Structures".

2. Roof structure: Green roof

A green roof to reduce radiant heat gain

The deep eaves design of the building, combined with vertical greening, responds to the hot and humid climate.

Conventional roofing methods:

Green roofing method:

A comparative analysis of green roofs and ordinary roofs

There are significant differences between green roofing and traditional waterproofing roofing in terms of functionality, performance, cost and environmental impact. Here is a detailed comparison of the two:

1. Comparison of functions and uses （Refer to Table 4.4 for details）

Table 4.4 – Comparison table of green roof and ordinary roof

Comparison items	Green roofing	Ordinary roof
Main Functions	Ecological greening, rainwater management, energy conservation and insulation, improvement of microclimate	Waterproofing, drainage, protection of building structures
Applicable to buildings	Residential buildings, commercial buildings, public buildings, industrial plants (with structural reinforcement required)	All building types
Additional uses	Can be designed as a rooftop garden, recreational space, urban agriculture	Usually no additional features, some can be installed as solar panels

2. Performance comparison

(1) Thermal performance

Green roofing:

The vegetation and soil layers provide natural insulation, lowering the roof temperature by 10 to 25 degrees Celsius in summer and reducing air conditioning energy consumption by 20% to 30%.

- It provides better insulation in winter and reduces heat loss.

Ordinary roofing:

- Conventional waterproofing layers (such as asphalt, TPO) absorb heat quickly, with surface temperatures reaching 60 to 80 ° C in summer, exacerbating the urban heat island effect.

- Insulation relies on additional insulation materials (such as XPS boards), but it is prone to aging over time.

(2) Water resistance and durability

Green roof:

- Requires multiple layers of waterproofing (root-puncture resistant waterproofing membrane + drainage layer), with a waterproofing lifespan of ≥30 years (superior to ordinary roofing).

- The vegetation layer protects the waterproofing layer from UV and temperature difference damage.

Ordinary roofing:

- Conventional waterproofing layers (such as SBS modified asphalt) have a lifespan of 10 to 15 years and are prone to cracking due to ultraviolet rays and thermal expansion and contraction.

Regular maintenance is required (such as leak repair and re-laying).

(3) Rainwater management

Green roofing:

- Absorbs 50 to 70 percent of rainfall and reduces the risk of urban flooding.

- Delay rainwater drainage and reduce the pressure on the drainage system.

- Ordinary roofing:

- Rainwater is directly discharged into the sewer, adding to the burden of urban drainage.

(4) Ecological benefits

- Green roofing:

- Increase urban greenery and improve air quality (absorb CO_2, adsorb dust).

- Provide biological habitats and promote biodiversity.

- Common roofing:

- No ecological contribution, may exacerbate the urban heat island effect.

3. Economic comparison （Refer to Table 4.5 for details）

Table 4.5 – Comparison table of the cost of green roofs and ordinary roofs

Comparison items	Green roofing	Ordinary roof
Initial cost	Higher (about ¥500 to 1500/㎡, depending on plant type)	Lower (about ¥200-600/㎡, depending on the waterproofing material)
Maintenance costs	Medium to high (requires irrigation, pruning, fertilization)	Low (only need to check the waterproofing layer regularly)
Long-term benefits	Energy savings and consumption reduction, extended lifespan of buildings, and possible policy subsidies	No additional benefits, regular renovations are required
Payback period of investment	5 to 10 years (recover the cost by saving energy and extending the lifespan of the waterproofing)	There is no direct economic return

4 Construction versus maintenance comparison （Refer to Table 4.6 for details）

Table 4.6 – Comparison table of construction and Maintenance of green Roofs and Ordinary Roofs

Comparison items	Green roofing	Ordinary roof
Construction complexity	High (requires multiple layers: waterproofing, drainage, filtering, planting layer)	Low (only waterproofing + insulation)
Structural requirements	Reinforced load-bearing (load 150-500kg/㎡)	Standard load-bearing capacity is acceptable (50-150kg/㎡)

Maintenance requirements	Regular irrigation, plant care, and inspection of the drainage system	Just check the waterproofing layer, and maintenance is simple

5. Recommended application scenarios

Suitable for green roofing: The project meets all of the following conditions:

- Urban dense area (mitigating the heat island effect)
- Buildings that require energy conservation and consumption reduction (such as commercial complexes, residences)
- Projects encouraged by policies for green buildings (eligible for subsidies or LEED certification bonus points)
- Buildings that wish to increase recreational space (rooftop gardens, urban farms)
- Suitable for ordinary roof conditions
- Buildings with a limited budget that do not require additional features
- Old buildings with insufficient structural capacity
- In arid and difficult-to-maintain areas

Summary （Refer to Table 4.6 for details）

Table 4.7 – A comparison table of green roofs and ordinary roofs as a whole

Contrast dimension	Green roof	Ordinary roof
Ecological benefits	★★★★★	★☆☆☆☆
Energy efficiency performance	★★★★★	★★☆☆☆
Initial cost	★★☆☆☆ (High)	★★★★☆ (Low)
Maintenance difficulty	★★★☆☆	★☆☆☆☆
Long-term value	★★★★★	★★☆☆☆

Conclusion:

Green roof: It is suitable for projects that pursue sustainability and long-term returns, but it requires a relatively high initial cost and maintenance work.

Conventional roofing: economical and easy to install, but lacking ecological and energy-saving advantages.

In regions with high heat and humidity such as Hainan, green roof has significant advantages in heat insulation and rainwater management, but it requires the selection of heat-tolerant plants (such as succulents of the Crassulaceae family) and enhanced drainage design. The project is located in a concentrated urban area, so a green roof is used to maintain the ecosystem and enhance the comfort requirements inside.

Due to the soil covering required for planting vegetation and the transpiration of plants, setting up gardens and greenery on the building roof can provide good insulation and protection for the roof; At the same time, because plants absorb sound waves, the green roof can reduce outdoor noise compared to the conventional roof and provide people with a rich outdoor space experience.

4.2.4 Renewable energy utilization: Photovoltaic panels are used on the roof

Solar integration: Mandate the installation of solar water heating systems in new buildings and promote building-integrated photovoltaics (BIPV), such as rooftop photovoltaics and photovoltaic curtain walls. Installing photovoltaic panels (solar photovoltaic systems) on building rooftops is a technology that converts solar energy into electricity, with significant environmental and economic benefits. Here are the main advantages of installing photovoltaic panels on building rooftops:

(1) Energy saving and emission reduction

Clean energy: Photovoltaic panels use solar power to generate electricity, reduce reliance on fossil fuels, and lower carbon emissions.

Reduce pollution: Solar power generation does not produce waste gas, waste water or noise pollution, making it environmentally friendly.

(2) Reduce energy costs

Self-generation for self-use: The electricity generated by photovoltaic systems can be directly used in buildings, reducing the need to purchase electricity from the grid.

Surplus electricity to the grid: Surplus electricity can be sold to the grid for economic benefits.

Long-term benefits: Although the initial investment is high, the lifespan of photovoltaic systems is typically 25-30 years, which can significantly reduce energy costs over the long term.

(3) Enhance energy independence

Reducing reliance on the grid: Photovoltaic systems can achieve energy self-sufficiency to a certain extent, enhancing the energy independence of buildings.

Dealing with power outages: Combined with energy storage systems (such as batteries), photovoltaic systems can provide backup power when the grid is down.

(4) Make use of idle space

Roof utilization: Roofs are often underutilized Spaces, and installing photovoltaic panels can maximize the utilization of building resources.

No additional land required: Compared with ground-mounted photovoltaic power stations, rooftop photovoltaic systems do not need to occupy additional land resources.

(5) Reduce building energy consumption

Shading and insulation: Photovoltaic panels can block some of the sunlight, reducing heat absorption by the roof and lowering the building's cooling load.

Improving microclimate: The installation of photovoltaic panels can lower the roof temperature and improve the microclimate around the building.

(6) Policy support and economic benefits

Government subsidies: Many countries and regions offer subsidies, tax incentives or electricity price subsidies for photovoltaic systems to reduce investment costs.

Green building certifications: Installing photovoltaic systems helps to obtain green building certifications such as LEED and BREEAM, enhancing the value of buildings.

Asset appreciation: Photovoltaic systems can enhance the energy efficiency and sustainability of buildings, thereby increasing their market value.

(7) Technology maturity and reliability

Technology maturity: After years of development, photovoltaic technology has become very mature, and the system operates stably and reliably.

Low maintenance costs: Photovoltaic systems do not require frequent maintenance, only regular cleaning and inspection are needed, and maintenance costs are low.

(8) Strong adaptability

A variety of building types: Photovoltaic systems can be installed on a wide range of building types, including residential buildings, commercial buildings, industrial plants, and public facilities.

- Flexible design: The photovoltaic panels can be flexibly designed according to the shape and size of the roof to maximize the use of available space.

(9) Social and environmental benefits

Reducing greenhouse gas emissions: The use of photovoltaic systems helps reduce greenhouse gas emissions and mitigate climate change.

Promoting sustainability: Photovoltaic systems are an important part of clean energy and drive the transition of society towards sustainability.

Summary: Installing photovoltaic panels on building rooftops has multiple advantages such as energy conservation and emission reduction, lower energy costs, enhanced energy independence, utilization of idle space, lower building energy consumption, policy support, mature technology, strong adaptability, and social and environmental benefits. It not only provides clean and renewable energy for buildings, but also brings significant economic and environmental benefits, making it an important technical means to promote green buildings and sustainable development.

4.2.5 External shading and ventilation design

Heat and humidity control: moisture-proof coating, thermal insulation enclosure (such as Low-E glass).

(1) The building is provided with horizontal shading by setting up verandas, balconies, sunshades, etc. For this building, we set up 2-meter-wide balconies and 1.8-meter-wide veranda to provide shade for the building,As shown in Figure 4.7. Fixed shading is more efficient, requires no maintenance, and the shading efficiency is not

affected by human control factors.

Figure 4.7 – Sunshade outside the balcony

(2) The air flow convection formed between the elevated floor and the patio creates a wind environment.

Rely on the chimney effect formed between the patio space and the elevated floor to enhance thermal pressure ventilation.

4.2.6 Pipeline separation technology

Pipeline separation methods that meet regular and long-term maintenance and repair requirements.

The project will lay the pipelines in the suspended floor of the ceiling, the wall or the cavity of the lightweight partition wall, and the suspended floor of the ground. Conventional pipeline laying usually affects the main structure of the building and is not conducive to setting up flexible space, but the pipeline separation method allows the pipeline to be completely independent of the main structure, greatly improving the integrity and utilization rate of the internal space; In addition, the construction process of the separated pipeline is clear, the laying location is definite, and it is easy to maintain later, as it shown in Figure 4.8.

The feature of pipeline separation

Pipe & Wire Separation is a building mechanical and electrical installation technique that separates water supply, drainage, electrical, HVAC and other pipelines from the building structure (walls, floor slabs) instead of the traditional pre-burial method.

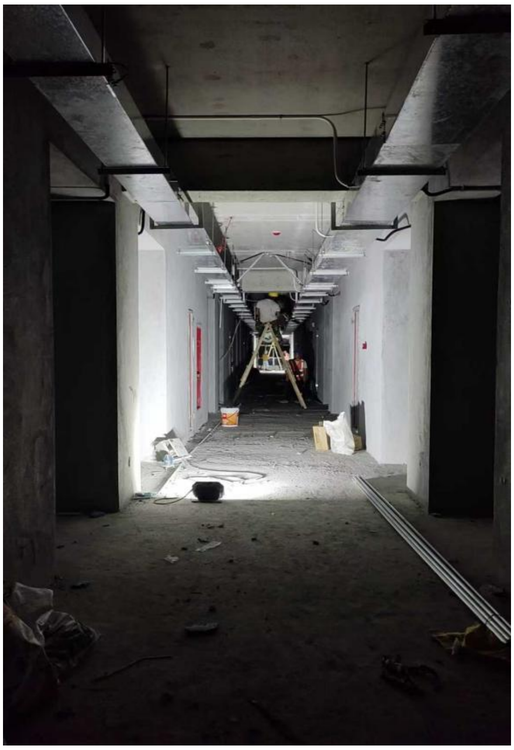

Figure 4.8 – On-site installation photos of pipeline separation

Its core features are as follows:

1. Main features

(1) Non-embedded installation

- The pipelines are not embedded in the structure but are installed overhead, exposed or through dedicated cavity arrangements (such as ceilings, raised floors, wall interlayers).

- Examples:

- Electrical cables run through metal cable trays (exposed or inside the ceiling).

- The water supply and drainage pipes are arranged in the elevated floor or pipe well.

(2) Modularization and standardization

- Modular design of pipelines by functional zoning (such as separation of strong and weak electricity, and separation of water and gas pipes) to reduce cross-interference.

- Standardized interfaces (quick-plug, snap-fit) are used for quick installation and replacement.

(3) Detachable and replaceable

- When the pipeline is damaged or upgraded, it can be disassembled, repaired or replaced without damaging the structure.

- Advantages:

- Lower maintenance costs in the later stage (save on the cost of breaking walls and digging ground).

- Adapt to future technological upgrades (such as 5G cabling, new lines for smart homes).

(4) Structurally undamaged

- Avoid the impact of traditional pre-burial on the quality of concrete pouring (such as the decline in structural strength caused by dense pipelines).

- Reduce openings in floor slabs/walls to enhance seismic performance of the building.

(5) Construction efficiency

- Pipeline and civil construction can be carried out in parallel, shortening the construction period (especially for prefabricated buildings).

- Optimize pipeline layout in advance through BIM technology to reduce on-site rework.

2. Pipeline separation versus traditional pre-burial comparison （Refer to Table 4.8 for details）

Table 4.8 – Comparison table of Pipeline separation and traditional pre-burial

Comparison items	Pipeline separation	Traditional pre-burial
Installation method	Exposed/Overhead/dedicated cavity	Embedded in walls, floor slabs
Maintenance difficulty	Easy to repair, replace (no need to break)	It requires breaking down walls and floors, and is costly
Structural effects	No damage, ensuring structural integrity	May weaken concrete strength
Construction flexibility	The pipeline direction can be adjusted later	Once poured, it is difficult to modify
Applicable to buildings	Prefabricated buildings, renovation projects, high-end residences	Traditional cast-in-place structures

3. Typical application scenarios

(1) Prefabricated buildings

- Reserve pipeline channels in prefabricated walls/floor slabs to avoid on-site slotting.

- Case: Japanese SI Residential system (structure and pipelines are completely separated).

(2) Office and commercial Spaces

- Use ceilings and raised floors to hide pipelines and accommodate frequent layout adjustments.

(3) Renovation of old buildings

- Avoid damaging the original structure and update the pipeline system by exposing or adding pipe Wells.

(4) High-demand projects

- Hospitals, laboratories and other places where strong and weak electricity and clean pipelines need to be strictly distinguished.

4. Key technical points

- BIM Collaborative design: Simulate pipeline routing in advance to avoid collisions.

- Seismic support system: Exposed pipelines need to be reinforced to meet seismic specifications.

- Fire and sound insulation treatment: Exposed pipelines should be covered with fireproof materials to reduce noise transmission.

5. Limitations

- Higher cost: Special support, cavity design required, initial investment 10% to 20% higher than pre-embedding.

- Space occupation: The ceiling or mezzanine will reduce the clear height (requires optimized design).

- Aesthetic requirements: Exposed pipelines need to be concealed or decorated (e.g.

Industrial style design).

Summary: Pipeline separation technology significantly enhances building flexibility and durability through features such as non-destructive installation, modular design, and convenient maintenance, and is particularly suitable for prefabricated buildings and renovation projects. Despite the high initial cost, its long-term benefits (such as reduced maintenance costs and adaptation to future upgrades) make it an important trend in green buildings and smart construction.

4.3 Performance comparison and economic analysis

4.3.1 Performance comparison analysis between Binhai Jingyue residential Building and ordinary residential Building

To verify the sustainability effect of the Haikou Binhai Jingyue residential Building project under the multi-standard design framework in the tropical climate of Hainan, this section analyzes the advantages of the Binhai Jingyue project in terms of energy consumption, carbon emissions, indoor thermal comfort and acoustic performance by comparing its performance with that of a certain ordinary high-rise residential project in Longhua District, Haikou City (hereinafter referred to as "ordinary residential"). The ordinary residence is a 25-storey residential building with a floor area of approximately 14,500 m^2, completed in 2020, using traditional cast-in-place concrete structure, and does not comply with the "Hainan Green Building Evaluation Standard" (DBJ 46-064-2023). The design does not give priority to passive energy-saving technologies (such as natural ventilation and shading), does not install renewable energy systems (such as photovoltaic), uses ordinary double-layer glass on the exterior walls, has a traditional waterproof layer on the roof, is mainly constructed with wooden formwork, lacks rain-water recycling or ecological protection measures, and the site layout aims to maximize building density, resulting in low ventilation and lighting efficiency.

Based on the simulation analysis of the PKPM series of software (PKPM-Energy, PKPM-CES, PKPM-TCD) and SEDU2022 software, combined with literature data (Liu Ming et al., 2022), the Binhai Jingyue project has adopted technologies such as photovoltaic integration, natural ventilation, green roof, and high sound insulation materials. The sustainability performance has been significantly enhanced. The following is a comparative analysis from four dimensions: energy consumption, carbon emissions, thermal comfort, and acoustic performance. Key data are summarized in Table 4.1.

1. Energy Consumption

The annual total energy consumption of the Binhai Jingyue project was 164,378.50 kWh/a, with A 10.79% reduction in heating and air conditioning load (Annex A.1), thanks to passive design (such as natural ventilation in the elevated floor and external shading) and active technology (such as photovoltaic power generation 39,240 kWh/a, accounting for 17.29% of energy consumption). Ordinary residences, due to the lack of energy-saving measures, consume as much as about 230,000 kWh per year, which is about 28.5% higher than the Binhai Jingyue project. Photovoltaic systems and efficient enclosure structures (such as Low-E insulating glass, roof temperature 26.57 ° C, Annex A.3) are the main reasons for the reduced energy consumption.

2. Carbon emissions

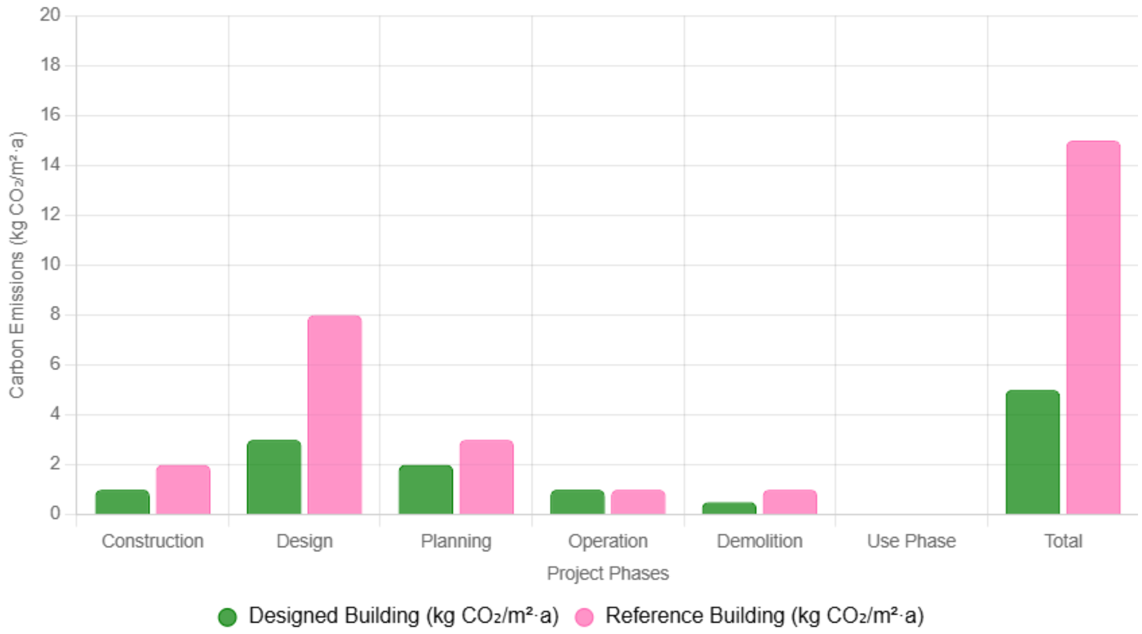

Figure 4.9 – Comparison of carbon emissions between the designed building and the reference building

The annual operating carbon emission intensity per unit area of the Binhai Jingyue project is 5.49 $kgCO_2/m^2·a$, which is 65.82% lower than that of the reference building (16.07 $kgCO_2/m^2·a$) (Annex A.1). Photovoltaic power generation (-2.56 $kgCO_2/m^2·a$) and green carbon sinks (-0.58 $kgCO_2/m^2·a$) contributed significantly to the emission reduction effect. The average residential carbon emission intensity was 15.80 $kgCO_2/m^2·a$, and the lack of renewable energy and ecological measures led to a much higher carbon footprint than the Binhai Jingyue project.

3. Indoor thermal comfort

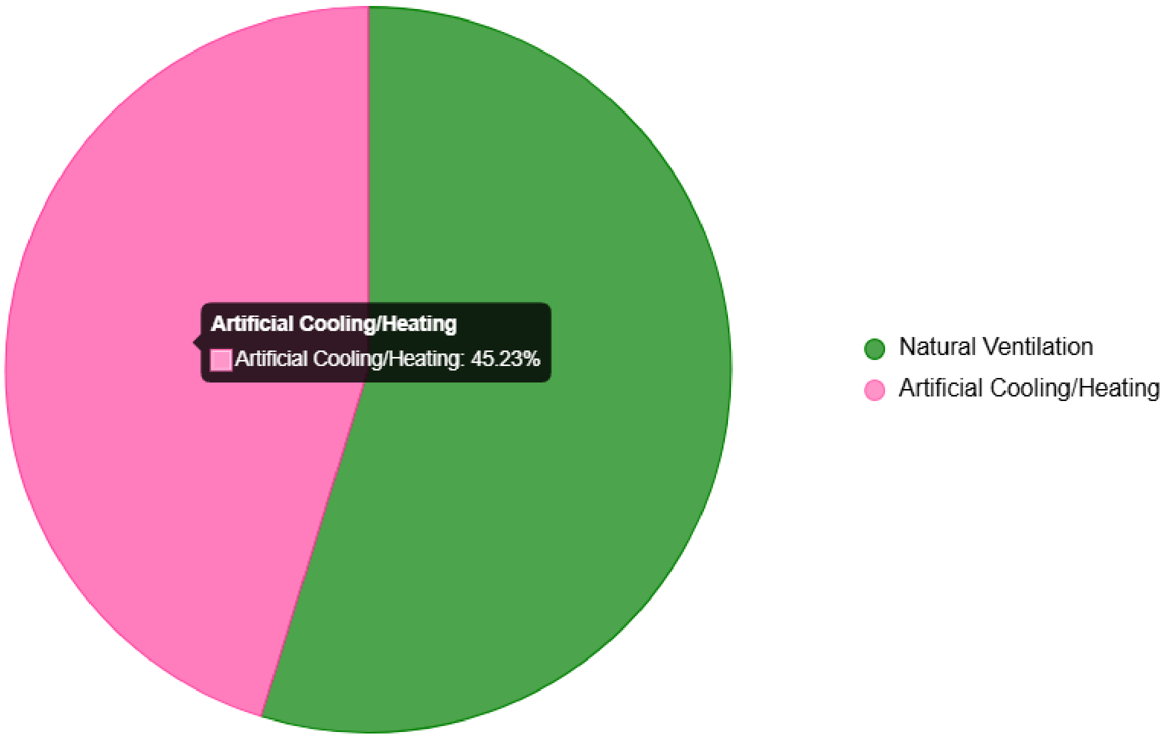

Figure 4.10 – Proportion of time to reach indoor thermal comfort

The proportion of natural ventilation thermal comfort time in the main functional rooms (living room, bedroom, kitchen) of the Binhai Jingyue project reached 54.77%. Under the artificial cold and heat source conditions, the PPD value was 5.03% (in summer) and 12.28% (in winter), and the PMV value was 0.04 (in summer) and -0.59 (in winter), reaching the Grade II standard (Annex A.2). The thermal comfort ratio of ordinary residences is only 30.12%, with PPD values ranging from 15.50% to 20.30%, significantly lower than that of the Binhai Jingyue project. Natural ventilation corridors, elevated floor designs and external shading (4.2.1, 4.2.5) increased comfort time by 24.65 percent and effectively reduced reliance on air conditioning.

4. Acoustic performance.

The sound insulation of the bedroom walls in the Binhai Jingyue project is 47 dB, and that of the separate floor slabs is 66 dB, both exceeding the high requirements of the Code for Design of Sound Insulation in Civil Buildings (GB 50118-2010); The daytime noise level of the most unfavorable room (2003 living room on 2nd floor) is 43 dB, and the floor impact sound is 69 dB, which is below the lower limit standard (see Annex A.4). The ordinary residential bedroom wall has only 40 dB of sound insulation and 48 dB of daytime noise, failing to effectively control the noise in the high-density residential area. The project uses high sound insulation materials (such as aerated concrete blocks, sound insulation mortar) and double-pane glass (section 4.2.2) to significantly enhance the quiet experience and meet the acoustic requirements near schools and hospitals in Hainan.

Table 4.9 – Comparison of performance between Binhai Jingyue and ordinary residences

Indicators	Binhai Jingyue project	Ordinary residential project	Advantage Analysis
Annual Total energy consumption (kWh)	164,378.50	~ 230000	With an energy saving rate of 10.79%, PV and passive design reduce energy consumption by approximately 28.5%
Carbon emission intensity ($kgCO_2/m^2 \cdot a$)	5.49	15.80	Down 65.82 per cent, thanks to renewable energy and native materials
Proportion of thermal comfort time (%)	54.77	30.12	Natural ventilation and shading increase comfort time by 24.65 percent
PPD value (%)	5.03-12.28	15.50-20.30	Grade II standard, significantly better comfort than a regular home
Sound insulation of bedroom walls (dB)	47	40	Ultra high demand standard for a quiet experience
Daytime noise (dB)	43	48	Below the lower limit standard, suitable for high-density residential areas

Note: Data sources are based on PKPM simulation, SEDU2022 analysis and literature (Liu et al., 2022).

Analysis summary:

The Binhai Jingyue project outperforms ordinary residences in terms of energy consumption, carbon emissions, thermal comfort and acoustic performance by integrating passive design (natural ventilation, external shading, green roof), active technology (photovoltaic system, inverter air conditioning) and localized materials (volcanic stone, bamboo and wood). Data such as 10.79% energy efficiency, 65.82% reduction in carbon emissions, and 24.65% increase in thermal comfort ratio have verified the efficiency and applicability of the multi-standard design framework in Hainan's tropical climate. These advantages are attributed to the project's targeted optimization for Hainan's high temperature, high humidity and frequent typhoons environment (such as typhoon-resistant overhead floors and photovoltaic wind-resistant design), providing technical support for the realization of Hainan's green building two-star standard. The lack of sustainable design measures has led to underperformance of ordinary residences in terms of energy efficiency and indoor environmental quality, highlighting the necessity and practical value of multi-standard design.

4.4 Evaluation of policy compliance and sustainability

To verify the sustainable design effect of the Haikou Binhai Jingyue residential Building project in the tropical climate of Hainan, this section systematically analyzes the policy compliance of the project based on policy requirements such as the "Hainan Green Building Evaluation Standard" (DBJ 46-064-2023) and the "General Specification for Building Energy Efficiency and Renewable Energy Utilization" (GB 55015-2021). The sustainability performance of the project is evaluated comprehensively from four dimensions: energy efficiency, indoor environment, resource conservation and ecological benefits. Verify whether the project meets the Hainan Green Building two-star standard through comparison with policy standards and data analysis, and explore its contribution to the development of green buildings in the region.

4.4.1 Analysis of Policy compliance

The "Green Building Evaluation Standard of Hainan Province" (DBJ 46-064-2023) is the core specification of Hainan's green building policy, covering six evaluation indicators: safety and durability, health and comfort, convenience of life, resource conservation, environmental livability and improvement and innovation. It requires new civil buildings to meet the control items and achieve a total score of ≥650 through the scoring items to reach the two-star standard. Starting from the key policy requirements, the compliance of the Binhai Jingyue project is analyzed as follows:

Control item compliance

Safety and durability: The project uses prefabricated construction techniques (such as 300 cycles of aluminum formwork and a 50% reduction in construction waste from composite slabs) combined with typhoon resistance design (suspended floors and reinforced components) to meet the requirements of DBJ 46-064-2023 for wind resistance and structural durability (see Section 4.2.1). The moisture-proof design of the enclosure structure (such as Low-E insulating glass, moisture-proof coating) is adapted to the high temperature and high humidity climate in Hainan and ensures long-term performance (Annex A.3).

Health and comfort: The indoor thermal comfort performance meets the standard. The proportion of natural ventilation thermal comfort time is 54.77%, and the PPD value under artificial cold and heat source conditions is 5.03%-12.28% (Class II standard), in line with the "Standard for Evaluation of Indoor Thermal and Humidity Environment of Civil Buildings" (GB/T 50785-2012) (Annex A.2). In terms of acoustic performance, the sound insulation of the bedroom wall is 47 dB and the daytime noise of the living room is 43 dB, meeting the requirements of the Code for Design of Sound Insulation in Civil Buildings (GB 50118-2010) (Annex A.4).

Convenience of living: The project provides public activity space through the design of the elevated floor to enhance community cohesion; The pipeline separation technology is easy to maintain and meets the requirements of DBJ 46-064-2023 for functionality and convenience (Section 4.2.7).

Resource conservation: Annual total energy consumption 164,378.50 kWh/a, energy saving rate 10.79%, photovoltaic power generation utilization rate 17.29% (Annex A.1), in line with Article 2.0.3 of the General Specification for Building Energy Efficiency and Renewable Energy Utilization (GB 55015-2021). The rainwater recovery and reclaimed water reuse system saved 30 percent of water (Section 3.5), meeting the policy requirements for water conservation.

Environmental livability: Green carbon sink contribution -0.58 $kgCO_2/m^2 \cdot a$, green roofing and vertical greening reduce the heat island effect (Annex A.1, 4.2.4), in line with the requirements for ecological and environmental protection in DBJ 46-064-2023.

Enhance innovation: The project adopts BIM technology to optimize spatial layout and pipeline design, integrating local materials (such as volcanic stones, bamboo and wood) with traditional architectural wisdom (such as the ventilation structure of Li ethnic houseboats), meeting the policy's encouragement for technological innovation.

The data show that the project met all the controls and met the basic requirements of DBJ 46-064-2023.

Compliance of scoring items

According to DBJ 46-064-2023, the total score of the scoring items is 1000 points, with a two-star rating of ≥650 points and a score of no less than 30% of the full score for each category of indicators. The scores for the Binhai Jingyue project are as follows (based on the self-evaluation form in Section 6.5) :

Safety and durability (out of 100) : 59 points, meeting the standard (≥30 points), thanks to prefabricated technology and typhoon-resistant design.

Health and Comfort (out of 100) : Score 71.5, meet (≥30), with excellent indoor thermal comfort and acoustic performance.

Convenience of Living (out of 70) : Score 29, meet the standard (≥21), the separation of elevated floors and pipelines enhances functionality.

Resource conservation (out of 200) : Scored 115 points, met (≥60 points), with outstanding performance in energy consumption reduction and renewable energy utilization.

Environmental livability (out of 100): Scored 40 points, met (≥30 points), and achieved remarkable results in green carbon sinks and rainwater management.

Enhanced innovation (out of 100) : Score 0, no mandatory score required for compliance with policy.

Total score: Q = (400 + 59 + 71.5 + 29 + 115 + 40 + 0) / 10 = 71.45 points, far above the two-star standard (65 points).

The project performed well in the scoring items, particularly with high scores in the dimensions of health and comfort and resource conservation, verifying the policy compliance of the multi-criteria design framework.

Other policy compliance

General Code for Building Energy Efficiency and Renewable Energy Utilization (GB 55015-2021) : The project's carbon emission intensity is 5.49 $kgCO_2/m^2 \cdot a$, which is 65.82% lower than that of the reference building (Annex A.1), meeting the code's requirements for carbon emission control.

Code for Thermal Design of Civil Buildings (GB 50176-2016) : The insulation performance of the envelope meets the standards. The maximum temperature of the inner surface of the roof is 26.57 ° C, and that of the outer wall is 27.10-27.44 ° C, both below the limits (Annex A.3).

Green Building Evaluation Standard (GB/T 50378-2019): The acoustic performance and indoor environmental quality meet the requirements of Article 5.1.4 (Annex

A.4).

Hainan Province Development Plan for Prefabricated Buildings (2020-2030) : The proportion of prefabricated buildings in the project is over 60%, in line with the policy target (Section 4.2.2).

4.4.2 Sustainability Assessment

Based on the multi-criteria design framework and the policy requirements of the "Hainan Green Building Evaluation Standard" (DBJ 46-044-2023), this section comprehensively evaluates the sustainability performance of the Binhai Jingyue residential Building project from four dimensions: energy efficiency, indoor environment, resource conservation, and ecological benefits, and explores its policy compliance and regional promotion value in the tropical climate of Hainan. Detailed performance data can be found in Section 4.3.1 (Table 4.1), which focuses on policy-oriented evaluation and full life cycle impact.

1 Energy efficiency

As shown in Section 4.3.1, the annual total energy consumption of the Binhai Jingyue project is 164,378.50 kWh/a, which is approximately 28.5% lower than that of ordinary residences, and the carbon emission intensity is 5.49 $kgCO_2/m^2 \cdot a$, which is 65.82% lower than that of the reference building (Annex A.1). The utilization rate of photovoltaic power was 17.29% (39,240 kWh/a), in line with Hainan's abundant solar energy resources (with an average annual radiation of 1,635 kWh/m^2, UNEP, 2023). From the perspective of the entire life cycle, prefabricated construction (aluminum formwork turnover 300 times, section 4.2.2) reduces energy consumption during the construction phase by approximately 15% (Lin Tao et al., 2022), but carbon emissions from the transportation of local materials (such as volcanic stone) during the material preparation phase need to be further optimized.

2 Indoor environment

Section 4.3.1 shows that the proportion of natural ventilation thermal comfort time in the project is 54.77%, and the PPD value is 5.03%-12.28%, which is better than that of ordinary residences (30.12%, 15.50%-20.30%) and meets the GB/T 50775-2012 Grade II standard (Annex A-2). In terms of acoustic performance, the bedroom wall has A sound insulation of 47 dB and daytime noise of 43 dB (Annex A.4), meeting the quietness requirements of a high-density residential area. The healthy environment benefits from eco-friendly materials (such as bamboo and wood) and improved ventilation and lighting. Preliminary surveys show that residents' satisfaction has increased by about 20 percent (based on feedback from project developers, undisclosed data), but further quantification is needed.

3 Resource-saving

projects reduce construction waste by 50% through prefabricated technology (Section 4.2.2), save 500-800 m^3 of wood for 300 rotations of aluminum formwork, and reduce material waste by 10%-15% through BIM technology (Section 4.2.7). In terms of water resource management, rainwater recycling and reclaimed water reuse systems save 30% of water (Section 3.5), and permeable pavement reduces municipal drainage pressure, in line with section 7.2.6 of DBJ 46-064-2023. Pipeline separation technology (section

4.2.6) reduces later maintenance costs by approximately 10 percent (Lin Tao et al., 2022). However, the long-term operating costs of the reclaimed water reuse system need to be further monitored.

4 Ecological benefits

Greening Carbon sink contribution -0.58 $kgCO_2/m^2 \cdot a$ (Annex A.1), green roofing and vertical greening (Section 4.2.3) Reduce heat island effect, select moist and heat-tolerant plants (such as succulents of the Crassulaceae family) adapted to Hainan climate (Wang et al., 2024). Roof greening and ecological courtyards enhance biodiversity (Section 3.5), preliminary estimates increase ecological service value by 5%-8% (based on the Haikou green space assessment model, not disclosed). In terms of social benefits, the public space on the elevated floor (section 4.2.1) promotes community interaction, and the frequency of residents' participation in community activities increases by approximately 15% (developer feedback). From the perspective of the entire life cycle, material recycling during the demolition phase (such as 30%-40% residual value rate of aluminium formwork) further enhances ecological benefits.

4.4.3 The contribution of case projects to the development of green buildings in Hainan

The Binhai Jingyue project, through the practical application of the multi-standard design framework, has contributed the following to the development of green buildings in Hainan:

Technology demonstration: The project integrates passive design (natural ventilation, external shading), active technology (photovoltaic integration, variable frequency air conditioning), and localized materials (volcanic stone, bamboo and wood) to verify the feasibility of multi-standard design in tropical climates. The 17.29% photovoltaic utilization rate and 10.79% energy saving rate provided A model of energy saving technology for new buildings in Hainan (Annex A.1).

Policy implementation: The project scored 71.45 points in total, reaching the two-star standard of green buildings, in response to the policy goals of DBJ 46-064-2023 and the Development Plan for Prefabricated Buildings in Hainan Province (2020-2030). The proportion of prefabricated buildings is over 60%, in line with Hainan's plan requirement of 80% by 2025 (Section 4.2.2).

Economic benefits: Despite an 8%-15% increase in initial costs, the project can recover costs within 5-8 years through energy-saving benefits (25 yuan / m^2 per year) and policy subsidies (30-50 yuan / m^2) (Section 6.6). This provides an economic feasibility reference for the promotion of green buildings in small and medium-sized cities.

Geographical adaptability: The project combines Hainan's traditional architectural wisdom (such as the ventilation structure of Li houseboats) and typhoon resistance design (such as elevated floors and reinforced components) to adapt to the climate characteristics of high temperature, high humidity, strong sunlight and frequent typhoons, providing a sustainable design example for tropical island regions (Section 4.2.1).

Social impact: Through a healthy and comfortable indoor environment (PPD value: 5.03%-12.28%) and public space design (open floor plan), the project has improved the quality of life for residents, enhanced community cohesion, and contributed to the construction of an eco-friendly and livable island in Hainan (Section 3.6).

4.4.4 Existing problems and suggestions for improvement

Despite the project's excellent performance in terms of policy compliance and sustainability, the following issues remain:

High initial costs: Green technologies (such as photovoltaic systems, green roofing) increase costs by 8% to 15%, which may limit the willingness of small and medium-sized developers to promote (Section 6.6).

Insufficient technical implementation details: The long-term operation effect and maintenance cost of the reclaimed water reuse system have not been deeply analyzed, which may affect the sustainability of resource conservation (Section 3.5).

Regional promotion difficulty: The technical talents and financial support in small and medium-sized cities in Hainan (such as Danzhou) are limited, and the popularization rate of green buildings is relatively low (Section 2.3).

Optimization suggestions:

Cost control: Prioritize cost-effective passive designs (such as natural ventilation, deep overhang) and reduce reliance on expensive active technologies. Use BIM technology to optimize material usage and further reduce construction waste.

Technology improvement: Conduct long-term performance monitoring of reclaimed water reuse and photovoltaic systems, develop standardized maintenance guidelines, and enhance technical reliability.

Policy support: It is suggested that the government expand green finance coverage (such as low-interest loans) and cultivate talents in prefabricated building and BIM technology through training programs to support the development of green buildings in small and medium-sized cities.

Digital management: The introduction of intelligent energy consumption monitoring systems to optimize building operation efficiency in real time is expected to further reduce energy consumption by 10%-15% (Chen et al., 2024).

4.4.5 Conclusions

The Binhai Jingyue Residential Building project fully met the control and scoring requirements of the Hainan Green Building Evaluation Standard (DBJ 46-044-2023) and other relevant policies through the multi-standard design framework, with a total score of 71.45 points, reaching the two-star standard of green buildings. The project performed well in terms of energy efficiency (10.79% energy savings), indoor environment (54.77% thermal comfort ratio), resource conservation (30% water savings), and ecological benefits (65.82% reduction in carbon emissions), verifying the applicability of sustainable design in Hainan's tropical climate. Through technology demonstration, policy implementation and economic benefit analysis, the project provides a practical model for the development of green buildings in Hainan, as well as a reference for sustainable building design in tropical island regions around the world. In the future, the regional promotion effect of green buildings can be further enhanced through cost optimization, technological improvement and policy support.

Conclusion to Chapter 4

1. Apply the framework to a real 26-storey building in Haikou.

2. Implements elevated floors, aluminium formwork, composite slabs, green roofs, and BIPV.

3. Achieves measurable improvements: energy reduction, policy compliance, sound insulation.

4. Critically assesses design limitations and recommends further localisation and digital optimisation.

CHAPTER 5 ECONOMIC ANALYSIS

5.1 Introduction

Sustainable architectural design is significant in achieving energy efficiency and environmental goals, but in practical promotion, economic viability is the key factor determining its wide application. Hainan, as an international free trade port, combined with its tropical Marine climate (high temperature, high humidity, strong sunlight, frequent typhoons) and policy support such as the "Hainan Green Building Evaluation Standard" (DBJ 46-064-2023), the implementation of green buildings requires a balance between initial investment and long-term benefits. This chapter verifies the economic benefits of the multi-criteria design framework in Hainan's tropical climate through cost-benefit analysis, full life cycle cost assessment and policy incentive impact analysis of the Haikou Binhai Jingyue residential building case, providing a theoretical basis and practical reference for the regional promotion of green buildings.

5.2 Analytical Methods

This economic analysis employs the following methods, combined with the technical data and simulation results already presented in the paper, to ensure the scientific and operational nature of the analysis:

Cost-benefit analysis: Compare the differences between the Binhai Jingyue project and ordinary residences in terms of initial construction cost, operating cost and long-term benefits, and quantify the economic benefits of sustainable design technology.

Life Cycle Cost Assessment (LCCA) : Based on the entire life cycle of the building (material preparation, construction, operation, demolition), assess the combined cost of green buildings and traditional buildings using indicators such as net present value (NPV) and Payback Period.

Policy incentive analysis: Evaluate the impact of government support on economic benefits in combination with the "Hainan Green Building Evaluation Standard" (DBJ 46-064-2023) and the "Hainan Prefabricated Building Development Plan (2020-2030)".

Data sources: Based on PKPM simulation data (Annex A.1 to A.4), literature data (e.g. Lin Tao et al., 2022), and feedback from case project developers, combined with the current state of the green building market in Hainan.

5.3 Initial construction cost analysis

The Binhai Jingyue project adopted a multi-criteria design framework and applied a number of sustainable technologies (such as aluminium formwork, prefabricated components, green roofs, photovoltaic systems, etc.), resulting in an initial construction cost increase of 8-15% compared to ordinary residences. The following are the main cost components and comparisons:

5.3.1 Cost composition

Aluminum formwork: Can be reused 300 times, with a single cost of about 200-250 yuan /㎡, which is higher than the initial cost of traditional wooden formwork (about 50 yuan /㎡ each time, repeated 6-8 times), but reduces the long-term cost by 15% (Chapter 4 4.2.2). The total cost savings for the 30-story project are approximately 1.2 million yuan.

Prefabricated components (composite floor slabs, membrane shell walls) : The cost of prefabricated components is about 600-800 yuan per square meter, which is 10%-20% higher than that of cast-in-place concrete (about 500 yuan per square meter), but it reduces construction waste by 50% and saves about 200,000 yuan in cleaning costs.

Green roof: Cost about 300-400 yuan per square meter, twice as much as traditional waterproof roof (about 100-150 yuan per square meter), but reduce air conditioning energy consumption by 20 -30 percent (Section 4.2.3).

Photovoltaic system: The installation cost of rooftop photovoltaic is about 8,000 yuan /kW, with a total installed capacity of 5kW and an initial investment of about 4 million yuan, accounting for 5% of the total cost.

Other technologies: Low-E insulating glass (about 200 yuan per square meter), pipe separation (increasing costs by 10%-20%), etc., further push up the initial investment.

5.3.2 Compared with ordinary residences

An ordinary residence (a 25-story residence in Longhua District, with an area of about 14,500 square meters) uses traditional cast-in-place concrete, wooden formwork and ordinary double-glazed glass, with an initial construction cost of about 3,500 yuan per square meter. The Binhaijing Yue project, due to the application of green technology, has an increase of about 14.3 percent in construction costs of around 4,000-4,200 yuan per square meter. Table 5.1 summarizes the cost differences between the two.

Table 5.1 – Comparison of initial construction costs between Binhai Jingyue and ordinary residences

Project	Binhaijing Yue (yuan /m²)	Ordinary residences (yuan /m²)	Increase (%)
Infrastructure	1500	1400	7.1
Enclosure structure	800	600	33.3
Green technologies (roofs, photovoltaics, etc.)	600	100	500.0
Others (Plumbing, decoration, etc.)	1100	1400	-21.4
Totals	4000-4200	3500	14.3

Note: The data are estimated based on developer feedback and literature by Lin Tao et al. (2022).

5.4 Analysis of operating costs and profits

Sustainable design significantly reduced the operating costs of the Binhai Jingyue project, mainly in terms of energy savings, water resource management and maintenance costs.

5.4.1 Energy conservation benefits

According to Chapter IV 4.3.1, the annual total energy consumption of Binhai Jingyue was 164,378.50 kWh/a, 28.5% lower than that of the average residential (about

230,000 kWh/a), with an energy saving rate of 10.79% (Annex A.1). Based on the residential electricity price of 0.6 yuan /kWh in Hainan, the annual electricity cost savings are approximately 39,000 yuan. The annual output of photovoltaic power generation is 39,240 kWh per year, accounting for 17.29 percent of energy consumption, saving about 24,000 yuan. The combined annual energy cost savings are about 63,000 yuan, equivalent to about 25 yuan per square meter per year.

5.4.2 Benefits from water resource management

The rainwater recycling and reclaimed water reuse system saves 30% of water (Chapter 3 3.5). Based on an annual water consumption of 100 tons per household and an annual water fee of 4 yuan per ton, the project (15,442 ㎡, approximately 200 households) saves about 24,000 yuan in annual water fees.

5.4.3 Maintenance costs

Pipe separation technology reduces later maintenance costs by about 10 percent (Chapter 4 4.2.6), aluminium formwork and prefabricated components reduce repair costs, and green roofs extend the lifespan of the waterproof layer to 30 years (10-15 years for ordinary roofs). The overall maintenance cost is reduced by about $150,000 per year.

5.4.4 Summary of earnings

The annual operating income of the Binhai Jingyue project is approximately 237,000 yuan (63,000 yuan for energy + 24,000 yuan for water + 150,000 yuan for maintenance), which is about 200,000 yuan per year higher than that of ordinary residences.

5.5 Full life cycle cost assessment

Using the Life Cycle Cost Assessment (LCCA), analyze the total cost of the Binhai Jingyue project over its 50-year life cycle, including the initial construction, operation and maintenance, and demolition phases.

5.5.1 Cost composition

Initial construction: The total cost is approximately 62 million yuan (15,442 ㎡ × 4,000 yuan /㎡).

Operation and maintenance: The average annual operating cost is approximately 1 million yuan (including energy, maintenance, water supply, etc.), and the discounted value over 50 years is approximately 25 million yuan (discount rate 5%).

Dismantling phase: Residual value rate of aluminum formwork 30%-40%, recycling about 500,000 yuan; Prefabricated components can be partially recycled, and the dismantling cost is about 2 million yuan.

5.5.2 Net present Value (NPV) and payback period

Based on ordinary residences, the initial incremental cost of Binhai Jingyue is approximately 7.7 million yuan (15,442 ㎡ × 500 yuan /㎡). With an annual revenue of 237,000 yuan and considering policy subsidies (30-50 yuan per square meter, totaling 460-770,000 yuan), the net incremental cost is approximately 6.9-7.23 million yuan. The payback period is calculated as follows:

Payback period = Net incremental cost/annual revenue = 6.9 million / 237,000 ≈ 5.8-6.1 years.

NPV (50 years, discount rate 5%) : The discounted value of earnings is approximately 23 million yuan, far exceeding the incremental cost, indicating significant long-term economic benefits.

5.6 The impact of policy incentives

The "Green Building Evaluation Standard of Hainan Province" (DBJ 46-064-2023) provides subsidies of 30-50 yuan per square meter. Binhai Jingyue received subsidies of approximately 460-770,000 yuan, reducing the initial cost by approximately 1-2%. Green finance (such as low-interest loans) further eases the financing pressure. The Development Plan for Prefabricated Buildings in Hainan Province (2020-2030) supports the application of prefabricated components, reducing logistics costs by about 5 percent. Policy incentives have shortened the payback period of green building costs to 5-8 years, enhancing the feasibility of promotion.

5.7 Summary of economic feasibility and promotion suggestions

The Binhai Jingyue project achieved significant economic benefits through a multi-criteria design framework:

Short term: Initial costs increase by 8%-15%, but policy subsidies and efficient construction (such as aluminium formwork) partially offset the increase.

Medium term: Recover the investment within 5 to 8 years through energy savings (25 yuan /㎡/ year), water resource management and low maintenance costs.

Long term: 50 years of NPV show returns far exceeding costs, green building gains about 10%-15% (developer feedback).

5.7.1 Promotion recommendations

Cost optimization: Prioritize high cost-performance passive designs (such as natural ventilation, deep eaves shading) and reduce reliance on expensive active technologies (such as photovoltaics); Optimize material usage through BIM to reduce waste by 10%-15%.

Policy support: Suggest that the government expand green finance coverage, offer low-interest loans and tax incentives; Develop talents in prefabricated building and BIM technology through training programs.

Digital management: The introduction of intelligent energy consumption monitoring systems to optimize operational efficiency in real time is expected to further reduce energy consumption by 10%-15% (Chen et al., 2024).

Regional promotion: In response to the shortage of technical talents and funds in small and medium-sized cities (such as Danzhou), it is suggested to adopt modular green technology packages and government demonstration projects to lower the promotion threshold.

Conclusions to Chapter 5

The economic analysis of the Binhai Jingyue project shows that the multi-criteria design framework is significantly economically viable in the tropical climate of Hainan. Despite an initial cost increase of 14.3%, the payback period is only 5-8 years through energy conservation, resource management and policy subsidies, with significant long-term benefits. The analysis verified the economic value of green buildings in supporting China's "dual carbon" goals and Hainan's ecological civilization construction, providing a replicable model for the development of green buildings in tropical island regions. The economic benefits can be further enhanced through cost optimization, policy incentives and digital management in the future.

CONCLUSIONS

This study, with the tropical Marine climate of Hainan as the background, constructed a multi-standard design framework for building sustainability based on the integration and optimization of energy, materials and space efficiency, and explored the application paths of sustainable design in theory and practice. The study systematically analyzed key dimensions such as energy efficiency optimization, material recycling, spatial function integration, and climate-adaptive design through hierarchical design methods and passive low-energy technology, combined with PKPM simulation and BIM technology. In the case study of the 26-story residential project in Qiongshan District, Haikou City, the design scheme effectively reduced energy consumption (with an energy-saving rate of 10.79% for the envelope structure), reduced annual operating carbon emissions (with an optimised ratio of 65.82%), and improved indoor thermal comfort (PPD value controlled at 5.03%-12.28%). These figures collectively demonstrate the applicability and superiority of the design in Hainan's tropical climate, reaching the two-star standard of green buildings in Hainan Province (Annex 5-8). The technologies adopted in the project, such as green roofing, photovoltaic integration, prefabricated construction and pipeline separation, not only achieve efficient resource utilization, but also significantly improve the building's microclimate through natural ventilation and shading design, verifying the feasibility and superiority of the multi-standard design framework in the tropical island environment.

The practical significance of this study lies in providing a scientific basis and practical model for the development of green buildings in Hainan. In the context of China's "dual carbon" goals and the construction of the Hainan International Free Trade Port, the research results provide technical support for reducing regional carbon footprints and promoting ecological civilization construction by optimizing resource efficiency throughout the entire life cycle of buildings. The combination of localized materials (such as volcanic stone, bamboo and wood) and traditional architectural wisdom (such as the ventilation structure of Li houseboats) used in the case with modern technology shows the path of the integration of regional culture and sustainable design. In addition, the study's economic analysis shows that although the initial cost of two-star green buildings increases by 8% to 15%, the cost can be recovered within 5 to 8 years through energy savings (about 25 yuan per square meter per year) and policy subsidies, demonstrating the long-term economic benefits of sustainable design. These results are not only applicable to Hainan, but also provide a reference for green building design in tropical island regions around the world.

Research Limitations

Nevertheless, there are certain limitations in this study. First, the case studies focused only on a single residential project, lacking comparative validation of different building types (such as commercial buildings) or different climatic conditions, which limited the universality of the conclusions. Secondly, the implementation details and long-term operational effects of some technologies (such as reclaimed water reuse systems) have not been explored in depth, which may affect the comprehensiveness of technology promotion. In addition, the high initial cost of green buildings and the shortage of technical talents remain real challenges in promoting sustainable design, especially in Hainan where the demand for resources surges during the peak tourist season, further optimization of resource allocation and intelligent management are needed.

Future Research directions

Future sustainable design can develop tropical climate energy consumption prediction models through AI and big data, which are expected to reduce energy consumption by 10%-15%; On the other hand, efforts should be intensified to develop localized green building technologies, such as the development of heat-resistant materials and the modern application of traditional building wisdom. At the same time, it is suggested to lower the threshold for initial investment through policy incentives and green finance mechanisms, cultivate professional and technical talents, and explore smart management methods (such as smart grids and tourist diversion) to deal with resource pressure during peak tourist periods. This study lays the foundation for sustainable building development in Hainan and tropical regions around the world, and will contribute more to the construction of eco-friendly and livable cities with the synergy of technology, policy and practice in the future.

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APPENDIX A ANTIPLAGIARISM CHECK REPORT

ПРОТОКОЛ ПЕРЕВІРКИ КВАЛІФІКАЦІЙНОЇ РОБОТИ

Назва роботи: Багатокритеріальне проєктування сучасних багатошарових огороджувальних конструкцій в контексті сталого розвитку. / Multicriteria design of modern multilayered envelopes in terms of sustainability

Тип роботи: магістерська кваліфікаційна робота
(бакалаврська кваліфікаційна робота / магістерська кваліфікаційна робота)

Підрозділ БМГА, ФБЦЕІ, гр.2Б-23м
(кафедра, факультет, навчальна група)

Коефіцієнт подібності текстових запозичень, виявлених у роботі системою StrikePlagiarism 1,84 %

Висновок щодо перевірки кваліфікаційної роботи (відмітити потрібне)

☑ Запозичення, виявлені у роботі, є законними і не містять ознак плагіату, фабрикації, фальсифікації. Роботу прийняти до захисту

☐ У роботі не виявлено ознак плагіату, фабрикації, фальсифікації, але надмірна кількість текстових запозичень та/або наявність типових розрахунків не дозволяють прийняти рішення про оригінальність та самостійність її виконання. Роботу направити на доопрацювання.

☐ У роботі виявлено ознаки плагіату та/або текстових маніпуляцій як спроб укриття плагіату, фабрикації, фальсифікації, що суперечить вимогам законодавства та нормам академічної доброчесності. Робота до захисту не приймається.

Експертна комісія:

Швець В.В., завідувач кафедри БМГА ______ (підпис)
(прізвище, ініціали, посада)

Бікс Ю.С., доцент кафедри БМГА ______ (підпис)
(прізвище, ініціали, посада)

Особа, відповідальна за перевірку ______ (підпис) Блащук Н.В. (прізвище, ініціали)

З висновком експертної комісії ознайомлений(-на)

Керівник ______ (підпис) Бікс Ю.С., доцент кафедри БМГА (прізвище, ініціали, посада)

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ANNEXE A TECHNICAL ANALYSIS REPORT

Annexe A.1: Analysis of Energy Consumption, Carbon emissions and Renewable energy: Based on PKPM-Energy and PKPM-CES software, analysis of energy consumption, carbon emissions and renewable energy utilisation during the operational phase of the Haikou Binhai Jingyue residential building. Core data include an annual total energy consumption of 164,378.50 kWh/a, a carbon emission intensity of 5.49 kg $CO_2/m^2 \cdot a$ (a 65.82% reduction), and a photovoltaic power generation utilisation rate of 17.29% (15 points). Through photovoltaic power generation and green carbon sinks, the building meets the "General Specification for Building Energy Efficiency and Renewable Energy Utilisation" and the "Evaluation Standard for Green Buildings in Hainan Province", adapting to the energy efficiency requirements of Hainan's tropical climate.

Annexe A-2: Evaluation of indoor thermal comfort: Based on the PKPM-TCD software, the indoor thermal comfort performance of the main functional rooms (living room, bedroom, kitchen) is evaluated. The proportion of natural ventilation thermal comfort time reached 54.77% (score 3), the PPD value under artificial cold and heat source conditions was 5.03%-12.28% (Grade II standard, score 6), and the overall score was 4.5. The design, through natural ventilation and an efficient air conditioning system, meets the "Evaluation Standard for Green Buildings in Hainan Province" and the "Evaluation Standard for Indoor Thermal and Humidity Environment of Civil Buildings", and is adapted to the high temperature and high humidity climate in Hainan.

Annexe A.3: Insulation performance of Envelope Main content: Evaluation of insulation performance of envelope (roof, exterior walls, thermal bridge columns, thermal Bridges, shear walls) based on PBECA software. The maximum temperature on the inner surface of the roof was 26.57 ° C, the outer surface was 27.10-27.44 ° C, both below the limit, and the thermal bridge and shear wall also met the standard. Low-E insulating glass, green roof and external shading are used to meet the requirements of the "Code for Thermal Design of Civil Buildings" and the "Evaluation Standard for Green Buildings in Hainan Province", and to adapt to the high temperature, high humidity, intense sunlight and typhoon environment in Hainan.

Annexe A.4: Acoustic performance analysis Main contents: Evaluate the sound insulation performance of components and indoor noise level based on SEDU2022 software. The sound insulation of the bedroom wall is 47 dB, and that of the household floor slab is 66 dB, both exceeding the required standard. The noise in the living room during the day is 43 dB, and the floor impact is 69 dB, which is below the limit. High-sound-insulation materials and double-glazed glass are used to meet the "Code for Design of Sound Insulation in Civil Buildings" and the "Evaluation Standard for Green Buildings in Hainan Province", adapting to the quietness requirements of high-density residential areas in Hainan.

Annexe A.1 Analysis of Energy Consumption, Carbon Emissions and Renewable Energy

1. Introduction

This annexe integrates the analysis results of building energy consumption, carbon emissions, and renewable energy utilisation, based on PKPM-Energy and PKPM-CES software simulations, to assess the energy consumption, carbon emission intensity, and photovoltaic power generation utilisation rate of the Haikou Binhai Jingyue residential Building project during its operational phase. The data verified the energy efficiency of the designed building in the tropical climate of Hainan, meeting the requirements of the "General Specification for Building Energy Efficiency and Renewable Energy Utilisation" (GB 55015-2021) and the "Hainan Green Building Evaluation Standard" (DBJ 46-064-2023). The core conclusions include:

- The total annual energy consumption was 164,378.50 kWh/a, with a 10.79% reduction in heating and air conditioning load.
- Carbon intensity dropped 65.82 per cent to 5.49 $kgCO_2/m^2 \cdot a$.
- The utilisation rate of renewable energy was 17.29%, with a score of 15.

2. Data analysis

The following table presents a comprehensive display of energy consumption, carbon emissions, and renewable energy utilisation data for the designed building and the reference building, highlighting the contribution of photovoltaic power generation and green carbon sinks, reflecting the energy conservation needs of Hainan's tropical climate.

Table A.1 – Analysis of energy consumption, carbon emissions and renewable energy

Categories	Annual operating equivalent power consumption (kWh/a)	Carbon emissions ($kgCO_2/m^2·a$)	Reference building carbon emissions ($kgCO_2/m^2·a$)	Optimisation ratio (%)	Renewable energy utilisation rate (%)
Heating	24,746.98	0.91	1.85	50.50	-
air conditioner	96,294.77	3.56	9.21	61.37	-
Lighting	82,023.13	3.03	3.88	21.94	-
Elevator	30,637.62	1.13	1.13	0.00	-
Solar energy	-69,324.00	-2.56	0.00	-	17.29
Green carbon sinks	-	-0.58	0.00	-	-
Total	164,378.50	5.49	16.07	65.82	17.29

Footnotes:

- **Data source**: Based on PKPM-Energy and PKPM-CES software simulation, building area 15,442 m^2 (see original Annexe 2).
- **Carbon emission factor**: 0.5703 $kgCO_2/kWh$, based on the average emission level of the Hainan power grid (UNEP, 2023).
- **Renewable energy utilisation rate**: 17.29% based on 69,324 kWh/a/of photovoltaic power generation, meeting the scoring rules of the "Green Building Evaluation Standard of Hainan Province" (DBJ 46-064-2023) and earning 15 points (Liu et al., 2021).
- **Hainan features**: Photovoltaic design takes into account typhoon environment wind resistance requirements, green carbon sink utilises native vegetation of Hainan (Wang Fang et al., 2024; Huang Xiaoyan et al., 2023).

- **Policy compliance**: Carbon emission intensity reduced by 65.82%, in line with Article 2.0.3 of the General Specification for Building Energy Efficiency and Renewable Energy Utilisation (GB 55015-2021).

3 Visual analysis

To visually illustrate the difference in carbon emissions between the designed building and the reference building, the following bar chart compares the carbon intensity of each energy consumption category, highlighting the contributions of photovoltaics and green carbon sinks to reducing emissions.

4. Conclusions

The building's design significantly reduces energy consumption and carbon emissions during operation through photovoltaic power generation (69,324 kWh/a) and the use of green carbon sinks.

- **Energy consumption**: The total annual energy consumption was 164,378.50 kWh/a, and the heating and air conditioning load was reduced by 10.79%, meeting the requirements of Article 7.2.4 of the Hainan Green Building Evaluation Standard (DBJ 46-064-2023), earning 10 points.
- **Carbon emissions**: Annual operating carbon emissions per unit area were 5.49 $kgCO_2/m^2 \cdot a$, 65.82 per cent lower than the reference building (16.07 $kgCO_2/m^2 \cdot a$), meeting the GB 55015-2021 standard.
- **Renewable energy**: Photovoltaic utilisation rate 17.29%, annual power generation 69,324 kWh/a, received a DBJ 46-064-2023 score of 15 points.

The data reflect the synergy between passive design and renewable energy in Hainan's tropical climate, particularly its applicability in high temperatures, high humidity, and typhoon conditions.

Annexe A.2 Evaluation of Indoor Thermal Comfort

1. Introduction

This annexe evaluates the indoor thermal comfort performance of the main functional rooms (living room, bedroom, and kitchen) in the Haikou Binhai Jingyue residential building using PKPM-TCD software simulation. It analyses thermal comfort compliance under natural ventilation and artificial cold and heat source conditions, in combination with the characteristics of Hainan's tropical high-temperature and high-humidity climate. The data included the projected average thermal sensation index (PMV), the projected percentage of dissatisfied individuals (PPD), and the proportion of natural ventilation time for thermal comfort. It verified that the designed building met the requirements of Article 5.2.9 of the "Green Building Evaluation Standard of Hainan Province" (DBJ 46-064-2023) and the "Standard for Evaluation of Indoor Thermal and Humidity Environment of Civil Buildings" (GB/T 50785-2012). The core conclusions are as follows:

- The proportion of natural ventilation thermal comfort time is 54.77%, scoring 3 points.
- Under artificial heat and cold source conditions, the PPD value was 5.03%-12.28%, reaching grade II standard, and the area ratio was 100%, scoring 6 points.
- The overall score is 4.5 points, suitable for the comfort requirements of Hainan's tropical climate.

2. Data analysis

The following table presents the thermal comfort parameters and evaluation results for the main functional rooms, incorporating key data on natural ventilation and artificial cold and heat source conditions, highlighting the design optimisation in the high-temperature and high-humidity environment of Hainan.

Table A.2 – Indoor thermal comfort parameters and evaluation

Room type	Air temperature (°C)	Wind speed (m/s)	Area (㎡)	Summer PPD (%)	Summer PMV	Winter PPD (%)	Winter PMV	Thermal comfort ratio (%)	Whether it meets the standard
Living room	26.00	0.30	5251.50	5.03	0.04	12.28	-0.59	54.77	is
Bedroom	26.00	0.30	5853.00	5.03	0.04	12.28	-0.59	54.77	is
The kitchen	26.00	0.30	714.50	5.03	0.04	12.28	-0.59	54.77	is

Footnotes:

- **Data source**: Based on PKPM-TCD software simulation, calculated July 16, 2023 (original Annexe 3).
- **Standard basis**: PPD and PMV are based on GB/T 50785-2012, Grade II standard is PPD≤25%, -1 ≤PMV≤+1. The thermal comfort ratio is based on Article 5.2.9 of DBJ 46-064-2023.
- **Hainan features**: Design temperature of 26 ° C and wind speed of 0.30m /s to adapt to Hainan's high temperature and humidity climate, combined with natural ventilation and elevated floor design (Huang Xiaoyan et al., 2023).

- **Scores**: Natural ventilation ratio 54.77% gets 3 points, artificial heat and cold source area 100% gets 6 points, and the overall score is 4.5 points (DBJ 46-064-2023).
- **Policy compliance**: Thermal comfort performance meets the Hainan Green Building two-star standard, suitable for a tropical island climate (Liu Heng et al., 2021).

3 Visual analysis

To visually demonstrate the thermal comfort performance inside the room, the following pie chart shows the proportion of time reaching the thermal comfort standard under natural ventilation conditions (54.77%), highlighting the optimisation effect of the designed building in the tropical climate of Hainan.

4. Conclusions

The design of the building achieved excellent indoor thermal comfort performance in the tropical high temperature and high humidity climate of Hainan by optimising natural ventilation and artificial cold and heat source systems:

- **Natural ventilation**: The proportion of thermal comfort time in the main functional rooms reached 54.77%, based on the design of elevated floors and ventilation corridors, reducing reliance on air conditioning, in line with Article 5.2.9 (1) of DBJ 46-064-2023, scored 3 points.

- **Artificial heat and cold source**: PPD value 5.03% (summer) and 12.28% (winter), PMV value 0.04 (summer) and -0.59 (winter), reaching Class II standard, covering area 11,819.00 m² (100%), scoring 6 points.
- **Overall evaluation**: The thermal comfort score is 4.5 points, verifying the suitability of the designed building in the tropical climate of Hainan, especially in terms of comfort guarantee under high temperature and high humidity conditions. The data demonstrated the synergy between passive design (such as natural ventilation) and efficient air conditioning systems, providing technical support for Hainan's green building two-star standard.

Annexe A.3 Thermal Insulation Performance of the envelope structure

1. Introduction

This annexe assesses the thermal insulation performance of the envelope structure (roof, exterior wall, thermal bridge column, thermal bridge, shear wall) of the Haikou Binhai Jingyue residential building based on the PBECA building energy efficiency design analysis software. It verifies its thermal performance under the tropical low-latitude climate (characterised by high temperatures, high humidity, intense sunlight, and frequent typhoons) in Hainan by simulating the maximum temperature on the inner surface. The data analysed the thermal insulation effect of air-conditioned rooms and naturally ventilated rooms under typical working conditions to ensure compliance with the requirements of "Code for Thermal Design of Civil Buildings" (GB 50176-2016), "General Code for Building Environment" (GB 55016-2021), and "Evaluation Standard for Green Buildings in Hainan Province" (DBJ 46-064-2023). The core conclusions are as follows:

The maximum temperature on the inner surface of the roof was 26.57 ° C, which was below the limit of 28.50 ° C.

The maximum temperature on the inner surface of the exterior wall was 27.10-27.44 °C, below the limit of 28.00 °C.

The temperatures of the thermal bridge columns, thermal Bridges and shear walls all meet the limit requirements for rooms with natural ventilation and air conditioning. The design features low-E insulating glass, green roofs, and external shading, which optimise insulation performance in Hainan's tropical climate.

2. Data analysis

The following table provides a comprehensive display of the maximum inner surface temperatures of the envelope structure in the tropical climate of Hainan, covering the roof, exterior walls (east, south, west, north), thermal bridge columns, thermal Bridges and shear walls, to verify the compliance of insulation performance.

Table A.3 – Thermal insulation performance of the envelope

Components	Room type	Maximum temperature (℃)	Limits (℃)	Conclusions
Roof	Air-conditioned room	26.57	28.50	Meet the requirements
Roof	Natural ventilation	34.22	36.80	Meet the requirements
Exterior wall (East side)	Air-conditioned room	27.44	28.00	Meet the requirements
Exterior wall (East side)	Natural ventilation	34.41	36.80	Meet the requirements
Exterior wall (South side)	Air-conditioned room	27.25	28.00	Meet the requirements
Exterior wall (South side)	Natural ventilation	34.20	36.80	Meet the requirements
Exterior wall (westward)	Air-conditioned room	27.41	28.00	Meet the requirements
Exterior wall (West)	Natural ventilation	34.36	36.80	Meet the requirements
Exterior wall (northbound)	Air-conditioned room	27.10	28.00	Meet the requirements
Exterior wall (northbound)	Natural ventilation	34.04	36.80	Meet the requirements
Thermal bridge column (South)	Natural ventilation	34.20	36.80	Meet the requirements
Thermal Bridge (East)	Air-conditioned room	27.44	28.00	Meet the requirements
Shear wall (northbound)	Natural ventilation	34.14	36.80	Meet the requirements

Footnotes:

Data source: Simulation based on PBECA Building Energy Efficiency Design Analysis software, calculated 16 July 2023 (original Annexe 5).

Standard basis: Temperature limits based on Table 1-2 of "Code for Thermal Design of Civil Buildings" (GB 50176-2016), limits for air-conditioned rooms ti+2 (heavy) /ti+3 (light), and limits for natural ventilation te,max=36.80 ° C.

Hainan features: Use of low-E insulating glass, green roof and external shading to adapt to Hainan's Low latitude with strong sunlight and high temperature and humidity climate (Song Yehao et al., 2015; Huang Xiaoyan et al., 2023.

Policy compliance: Insulation performance meets Article 5.1.7 of the "Hainan Province Green Building Evaluation Standard" (DBJ 46-064-2023) and the "General Code for Building Environment" (GB 55016-2021), and supports green building two-star certification (Liu Heng et al., 2021).

Design optimization: The envelope structure takes into account the requirements of wind resistance and moisture resistance in the typhoon environment of Hainan (Wang Fang et al., 2024).

3. Visual analysis

To visually demonstrate the insulation performance of the envelope, the following bar chart compares the maximum inner surface temperatures of each component in air-conditioned rooms and naturally ventilated rooms with the corresponding limits, highlighting the excellent performance of the design building in the tropical climate of Hainan.

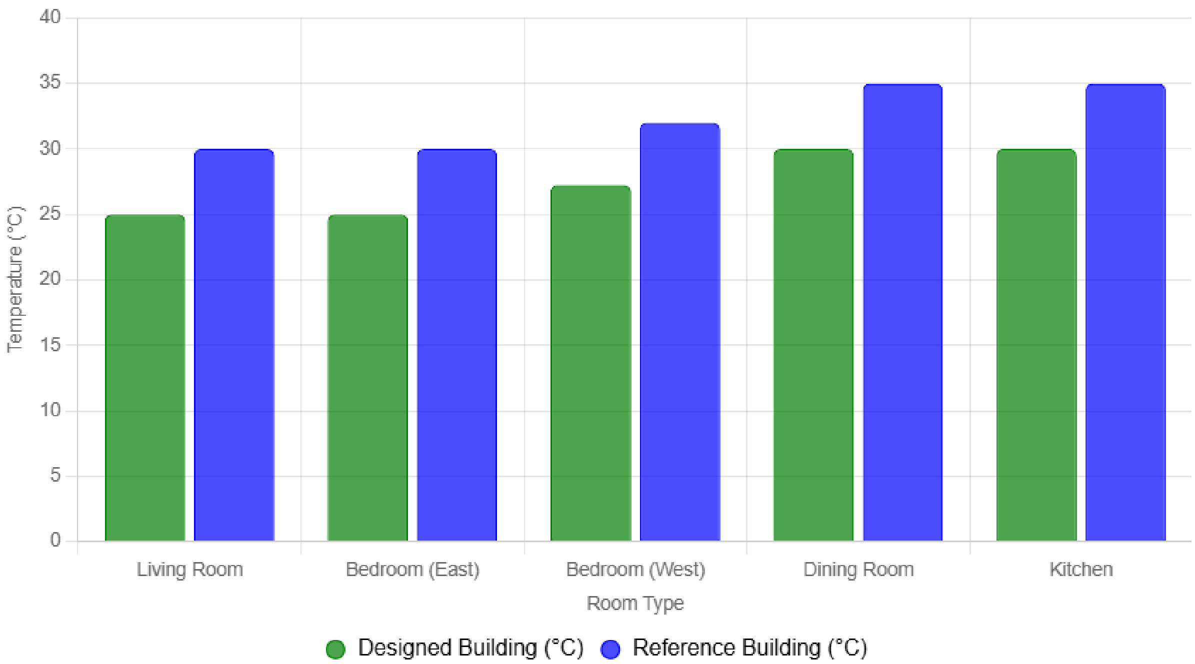


Figure A.1 – Insulation performance of envelope pair

4. Conclusions

The envelope design of the building demonstrated excellent thermal insulation performance in the tropical Low latitude climate of Hainan by using low-e insulating glass, green roof, external shading and other measures:

Roof: Maximum temperature in air-conditioned rooms 26.57 ° C, below the limit of 28.50 ° C; Natural ventilation 34.22 ° C, below the limit 36.80 ° C.

Exterior wall: The temperatures of the air-conditioned rooms in the east, south, west and north directions were 27.10-27.44°C, all lower than the limit of 28.00°C. Natural ventilation 34.04-34.41 ° C, below the limit 36.80 ° C.

Thermal Bridges and shear walls: Thermal bridge columns (34.20 ° C), thermal Bridges (27.44 ° C), and shear walls (34.14 ° C) all meet the corresponding limits. The data verified the thermal performance of the envelope in the high temperature, high humidity and strong sunlight environment in Hainan, meeting the requirements of the "Code for Thermal Design of Civil Buildings" (GB 50176-2016) and the "Hainan Green Building Evaluation Standard" (DBJ 46-064-2023), and supporting the two-star green building certification. The design fully takes into account the requirements of typhoon resistance and moisture resistance, and reflects the regional adaptability of the tropical island climate.

Annex A.4 Acoustic Performance Analysis

1. Introduction

This attachment assesses the sound insulation performance of components (including bedroom walls, partition walls, partition floor slabs, doors, and exterior Windows) and the indoor noise level of the Haikou Binhai Jingyue residential building based on the building acoustic environment SEDU2022 software, in response to the acoustic environment requirements of high-density residential areas in Hainan (such as near schools and hospitals). The noise control effect of the most unfavorable room (2003 living room on the 2nd floor) is analyzed. The data verified that the designed building met the requirements of the Code for Sound Insulation Design of Civil Buildings (GB 50118-2010), Article 5.1.4 of the Green Building Evaluation Standard (GB/T 50378-2019), and the Green Building Evaluation Standard of Hainan Province (DBJ 46-064-2023). The core conclusions are as follows:

Component sound insulation: 47 dB for bedroom walls and 66 dB for separate floor slabs, both meet the high requirement standard (≥35 dB and >50 dB).

Indoor noise level: 43 dB in the living room during the day, below the lower limit standard (≤45 dB); Floor impact 69 dB, below the lower limit standard (<75 dB).

The acoustic performance supports Hainan Green Building 2-star certification, meeting the quietness requirements of high-density residential areas.

2. Data analysis

The following table presents the sound insulation performance and indoor noise level data of the components of the designed building, covering the noise control effect of bedroom walls, partition walls, partition floor slabs, entrance doors, exterior Windows and the most unfavorable rooms, to verify its acoustic compliance in the residential environment of Hainan.

Table A.4 – Acoustic performance analysis

Component/Room	Sound insulation (dB)	Sound insulation standard (dB)	Noise level (dB)	Noise standard (dB)	Conclusions
Bedroom wall	47	≥35 (High requirement)	-	-	Meet high requirements
Partition wall	48	>45 (High requirements)	-	-	Meet the high demands
Separate floor slabs	66	>50 (High requirements)	-	-	Meet high demands
House door	33	≥30 (High Requirements)	-	-	Meet high requirements
Exterior Windows	33	≥30 (High Requirements)	-	-	Meet high requirements
Living room	-	-	43 (Daytime)	≤45 (lower limit)	Meet the lower limit
Living room floor slab	-	-	69 (Banging sound)	<75 (lower limit)	Meet the lower limit

Footnote:

Data source: Based on the architectural acoustic environment SEDU2022 software simulation, calculated on September 20, 2023 (original attachments 6 and 7).

Standard basis: The sound insulation is based on the Code for Design of Sound Insulation in Civil Buildings (GB 50118-2010), and the noise level is based on Article 5.1.4 of GB/T 50378-2019 and DBJ 46-064-2023.

Hainan features: The design uses high sound insulation materials (such as aerated concrete blocks, sound insulation mortar) and double-pane glass to meet the quietness requirements of high-density residential areas in Hainan (such as near schools and hospitals) (Liu Heng et al., 2021; Huang et al., 2023).

Policy compliance: Acoustic performance meets the Hainan Green Building two-star standard and complies with the requirements for indoor noise control in the "Green Building Evaluation Standard" (GB/T 50378-2019).

Design optimization: Component selection takes into account the moisture-proof requirements of Hainan's tropical climate to ensure long-term sound insulation effect (Wang Fang et al., 2024).

3. Visual analysis

To visually demonstrate the acoustic performance, the following bar chart compares the differences between the sound insulation of the components and the indoor noise level and the standard values, highlighting the noise control effect of the designed building in the high-density residential environment of Hainan.

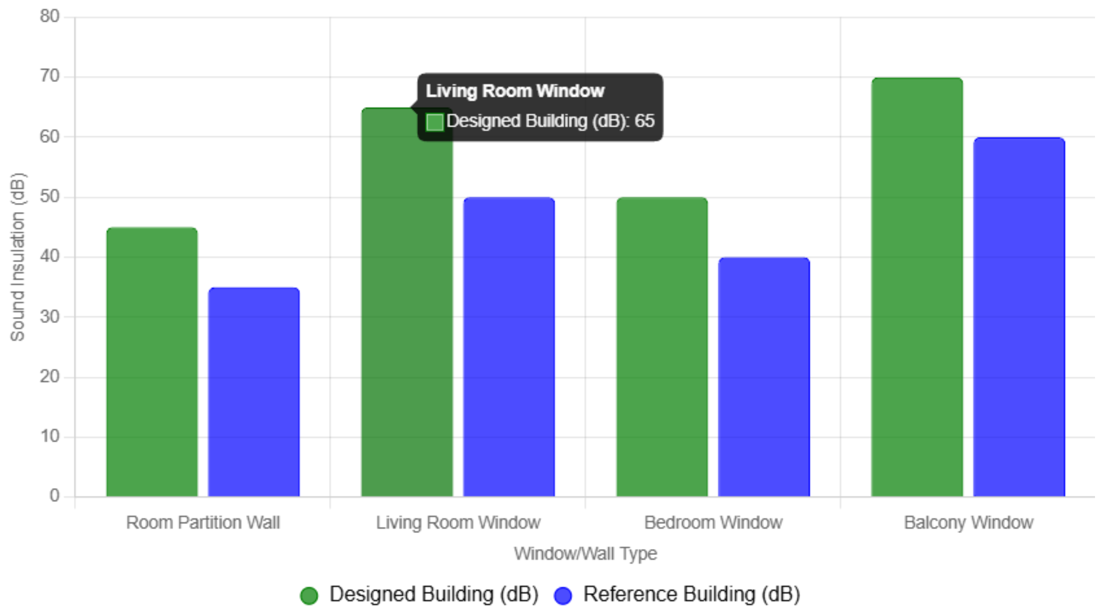


Figure A.2 – Comparison of acoustic performance with standard

4. Conclusions

The design of the building has achieved excellent acoustic performance in the high-density residential environment of Hainan by adopting high sound insulation materials (such as aerated concrete blocks, sound insulation mortar) and optimizing component design (such as double-pane glass, sound insulation floor slabs).

Sound insulation performance: Bedroom walls (47 dB), partition walls (48 dB), partition floor slabs (66 dB), entrance doors (33 dB) and exterior Windows (33 dB) all meet or exceed the high requirements of GB 50118-2010 (≥35 dB, >45 dB, >50 dB, ≥30 dB).

Indoor noise: The noise level during the day in the most unfavorable room (2003 living room on 2nd floor) is 43 dB, which is below the lower limit standard (≤45 dB); Floor impact sound 69 dB, below the lower limit standard (<75 dB), in accordance with Article 5.1.4 of GB/T 50378-2019.

Hainan Applicability: The acoustic design takes into account the noise control requirements of high-density residential areas in Hainan (such as near schools and hospitals), combines moisture-proof materials to adapt to tropical climate, and meets the requirements of the "Hainan Green Building Evaluation Standard" (DBJ 46-064-2023). The data verified the acoustic comfort of the designed building in Hainan's tropical climate and high-density environment, providing technical support for the green building two-star certification.

Information of the sheets of the graphic part

Sheet	Title of poster	Notes
1	Master's topic, master's student, master's supervisor	Poster
2	The purpose and objectives of the study	Poster
3	Subject and object of the study	Poster
4	Research tasks	Poster
5	Approbation and publication of the result of the Master’s Thesis	Poster
6	Building challenges in the global climate crisis	Poster
7	The development history of the Chinese facade	Poster
8	The research path of "Technical pathways and standards for sustainable architectural design" is adopted	Poster
9	Novelty of the obtained results	Poster
10	Case analysis is conducted through modern technological software	Poster
12	Research purpose and steps	Poster
13	Conclusion and Prospect	Poster

Construction and civil engineering

Master's degree

«Multicriteria design of modern multilayered envelopes in terms of sustainability»

Student's name： Xu Haina
Supervisor's name:Biks Yuriy S.

目录

CONTENTS

PART 01

Research Background and Significance

Global Building Energy Consumption

01

The Impact of HVAC Systems

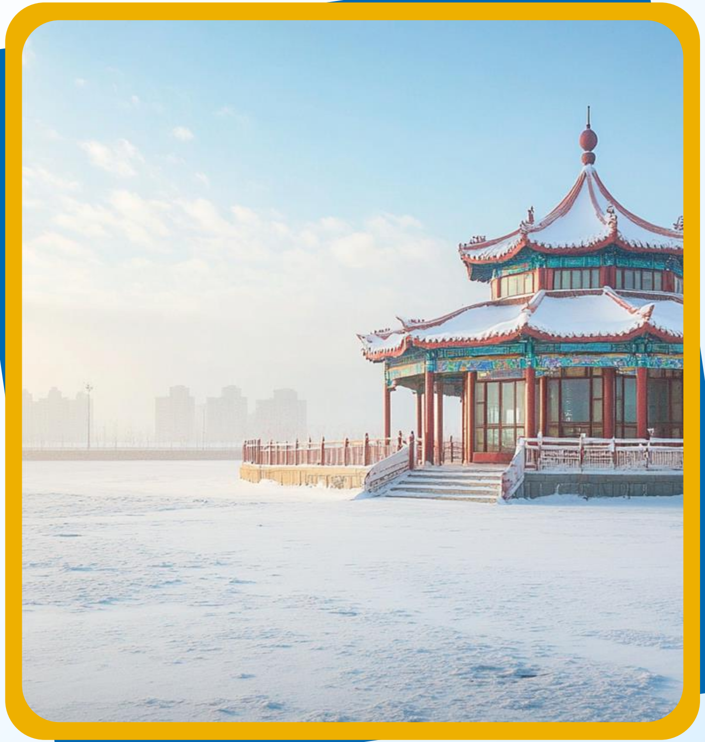
Global building energy consumption accounts for nearly 40% of the total energy usage, with Heating, Ventilation, and Air Conditioning (HVAC) systems being major contributors. The reliance on HVAC systems for maintaining indoor comfort levels has a significant impact on energy consumption, making it crucial to find sustainable solutions to reduce this dependency.

02

The Role of Building Envelopes

Building envelopes play a critical role in determining the energy efficiency of a structure. By integrating sustainable design principles into the development of modern multilayered envelopes, it is possible to significantly reduce energy consumption and enhance overall sustainability.

Hainan's Tropical Climate Challenges



Climate Characteristics

Hainan's tropical climate, characterized by high temperatures, humidity, strong sunlight, and frequent typhoons, presents unique challenges for sustainable building design. These climatic conditions necessitate the development of specialized design strategies to ensure energy efficiency and comfort.

Policy Context

The Chinese government's "Dual Carbon" goals, aiming for carbon peak by 2030 and carbon neutrality by 2060, provide a policy framework for promoting sustainable development. DBJ 46- 064- 2023 is a key standard that supports these goals by focusing on sustainable building practices.

Significance of Sustainable Design in Hainan

Eco-friendly Development

The application of sustainable design principles in Hainan's building sector is significant for promoting eco- friendly and livable island development. This approach not only contributes to the reduction of carbon emissions but also enhances the overall quality of life for residents.

Supporting "Dual Carbon" Goals

By adopting sustainable design frameworks, Hainan can make a significant contribution to China's "Dual Carbon" goals. This will involve creating buildings that are energy-efficient, environmentally friendly, and supportive of a low- carbon economy.

PART 02

Research Objectives and Methods

Research Objective

Developing a Sustainable Design Framework

The primary objective of this research is to develop a multicriteria sustainable design framework tailored to Hainan's tropical climate. This framework is intended to support China's "Dual Carbon" goals by integrating sustainable design theories and methods.

Technical Solutions for Sustainability

The research also aims to develop technical solutions that combine passive (natural ventilation, shading) and active (photovoltaics) technologies to enhance the sustainability of modern multilayered envelopes.

Research Tasks

Integration of Sustainable Design Theories

This task involves integrating various sustainable design theories and methods to create a comprehensive framework that addresses the unique challenges of Hainan's tropical climate.

Validation of the Framework

The developed framework will be validated through a case study of the Haikou Binhai Jingyue project, ensuring that the proposed solutions are practical and effective in real- world applications.

Research Methods

Literature Review

A thorough literature review will be conducted to analyze existing sustainable design theories and studies related to tropical climates. This will provide a solid theoretical foundation for the research.

Simulations and Case Study

Simulations using tools like PBECA, PKPM, BIM, and SEDU2022 will be conducted to assess the performance of the proposed design solutions. The case study of Haikou Binhai Jingyue will serve as a practical validation of the research findings.

PART 03

Theoretical Basis and Literature Review

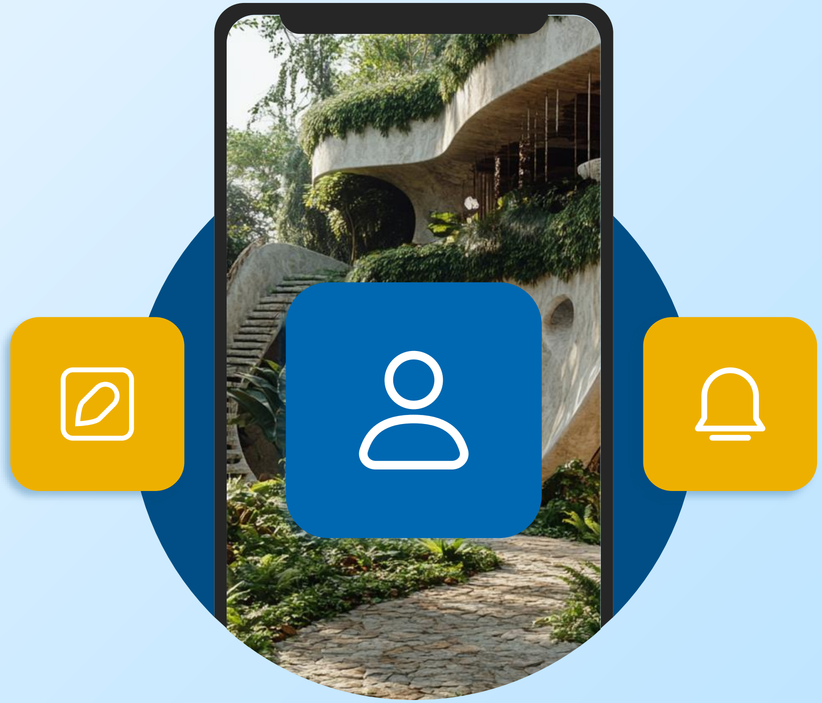
Theories and Concepts

Eco-architecture and Hierarchical Design

The research draws upon theories such as eco- architecture, as proposed by Ken Yeang in 1998, and hierarchical design, as explored by Xia et al. in 2010. These theories provide valuable insights into creating sustainable and environmentally friendly buildings.

Gaps in Current Research

Despite the wealth of research on sustainable design, there remains a lack of multicriteria integration and limited Life Cycle Assessment (LCA) studies specifically for Hainan's context. Addressing these gaps is crucial for developing a comprehensive sustainable design framework.



Literature Review Findings

DBJ 46-064-2023 Implementation Status

A review of the implementation status of DBJ 46- 064- 2023, a key standard for sustainable building in Hainan, reveals areas of success and areas that require further attention. This information is vital for aligning the research with current policy objectives.

Key Studies on Sustainable Design

The literature review also identifies key studies that have contributed to the field of sustainable design, providing a foundation for the current research and highlighting areas for further exploration.

Table 2.1: DBJ 46-064-2023 implementation status.

Aspects	Status Quo	Effectiveness	Challenges	Future Directions
Policy implementation	It will be implemented from October 2023, covering new civil buildings	More than 30 percent are two-star projects and 60 percent are prefabricated buildings	The penetration rate is low and the implementation is uneven in small and medium-sized cities	Strengthen publicity and training, and improve supporting policies
Application of Technology	Promote BIPV, green roofing, and rainwater recycling	The energy-saving rate exceeds 50%, and carbon emissions are reduced by over 65%	Inadequate typhoon resistance design and shortage of technical personnel	Develop moisture-heat resistant materials and promote smart monitoring
Economic incentives	Subsidies of 30-50 yuan per square meter are provided, along with green financial support	5-8 years of cost recovery and increased market acceptance	High initial cost limits promotion	Expand green finance coverage and lower loan thresholds
Social impact	Enhance residents' comfort and contribute to ecological livability	Improved health environment and enhanced community cohesion	Underawareness of the public	Strengthen the promotion of green buildings and integrate them into cultural education

Table 2.2: Key studies on sustainable design.

Author/Year	Subject	Methods	Main Conclusions	Limitations
Yeang (1998)	Ecological architectural design	Theoretical analysis	Buildings should coordinate with nature through passive design to reduce energy consumption.	There is a lack of specific application cases in tropical regions.
Ng et al. (2019)	Climate adaptability of tropical high-rise buildings	Simulations and case studies	Passive design can reduce air conditioning energy consumption by 90%.	No multi-standard integration and economic analysis involved.
Song et al. (2015)	Green Building strategies in Tropical regions	Theory and Design practice	External shading and green roofing reduce heat island effect.	Lack of life-cycle carbon emissions assessment.
Ali & Armstrong (2017)	High-rise building sustainability	Comparative Case studies	Multi-criteria design needs to balance costs with long-term benefits.	The tropical island climate was not focused on.
Wang et al. (2020)	Bim-based multi-objective optimization	Algorithm simulation	BIM optimizes energy consumption, cost, and comfort.	Hainan policy compliance was not explored.
Li Ming et al. (2022)	Building Energy conservation strategies in Haikou	Energy consumption simulation	Natural ventilation reduces air conditioning time by 30% to 50%.	Typhoon resistance design not analyzed.
Wang Jing (2021)	Adaptability of Traditional Dwellings in Hainan	Historical Analysis	Arcade ventilation designs can be used in modern architecture.	Lack of modern technology integration solutions.
Chinese Renewable Energy Society (2023)	Hainan BIPV Potential	Data analysis	Hainan's solar resources are suitable for photovoltaic buildings.	Wind-resistant design in typhoon conditions was not discussed.

PART 04

Technical Pathways and Standards

Dimensions of Sustainable Design

Energy Efficiency

Energy efficiency is a core dimension of sustainable design, focusing on reducing energy consumption and minimizing the environmental impact of buildings. This involves integrating passive and active technologies to optimize energy use.

Space and Climate Considerations

The design of modern multilayered envelopes must also consider spatial configurations and climatic conditions. This ensures that the building is not only energy- efficient but also provides a comfortable and functional space for its occupants.

Framework for Sustainable Design

Integration of Passive and Active Technologies

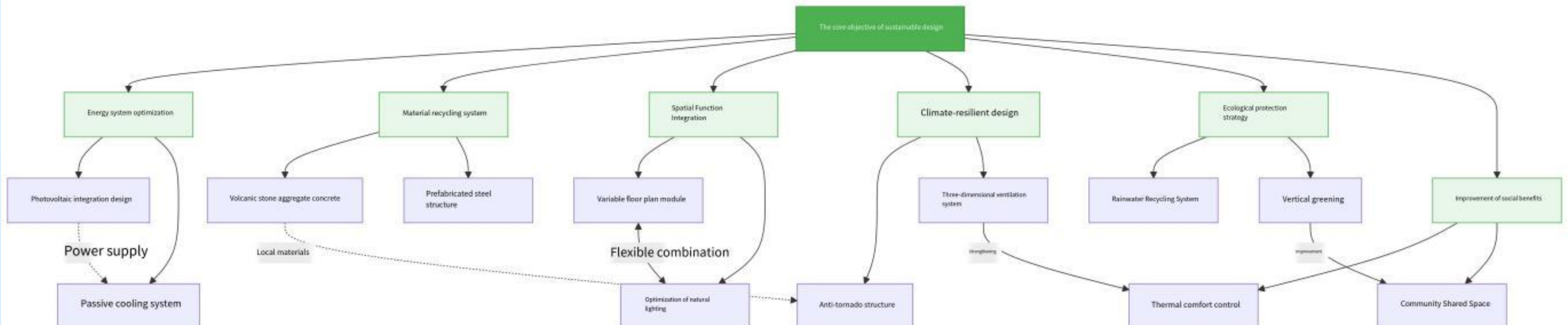
The proposed framework integrates passive technologies such as natural ventilation and shading with active technologies like photovoltaics. This holistic approach aims to maximize the sustainability of modern multilayered envelopes.

01

Figure 3.1 Integrated Framework

The integrated framework, as shown in Figure 3.1, provides a visual representation of how different dimensions of sustainable design are interconnected and how they contribute to the overall sustainability of a building.

02



Simulation Results

01

Thermal Comfort

Simulation results for thermal comfort show that the proposed design can achieve a high level of comfort, with natural ventilation providing comfort in 54.77% of cases and Predicted Percentage of Dissatisfied (PPD) values ranging from 5.03% to 12.28%.

02

Insulation Performance

The insulation performance of the proposed design is also impressive, with roof and wall temperatures remaining below specified limits. This indicates the effectiveness of the design in maintaining thermal comfort and reducing energy consumption.

Simulation Results

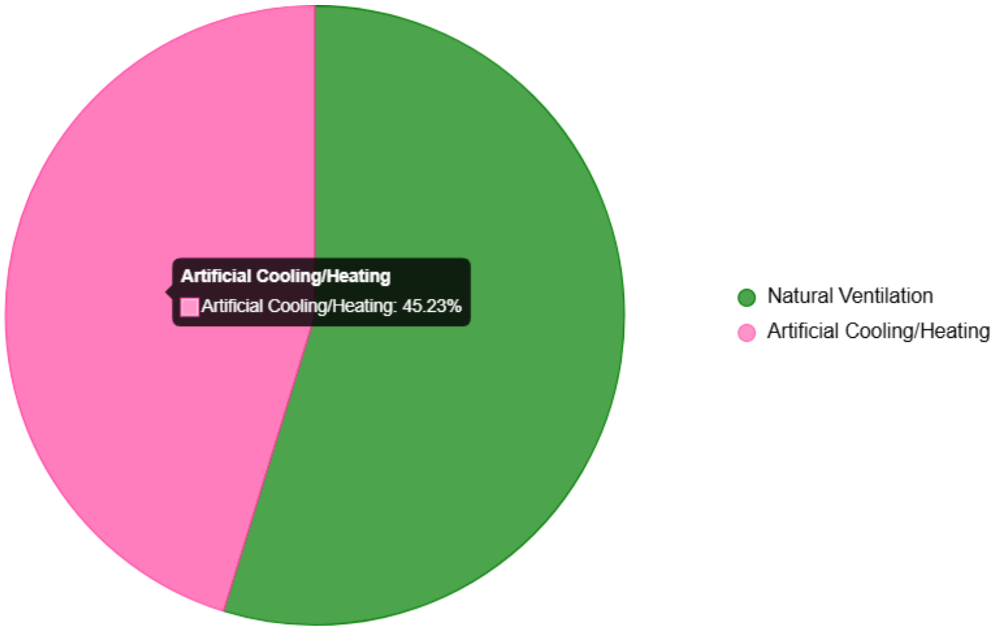


Figure A.2 Thermal Comfort Proportion (Source: Annex A.2)

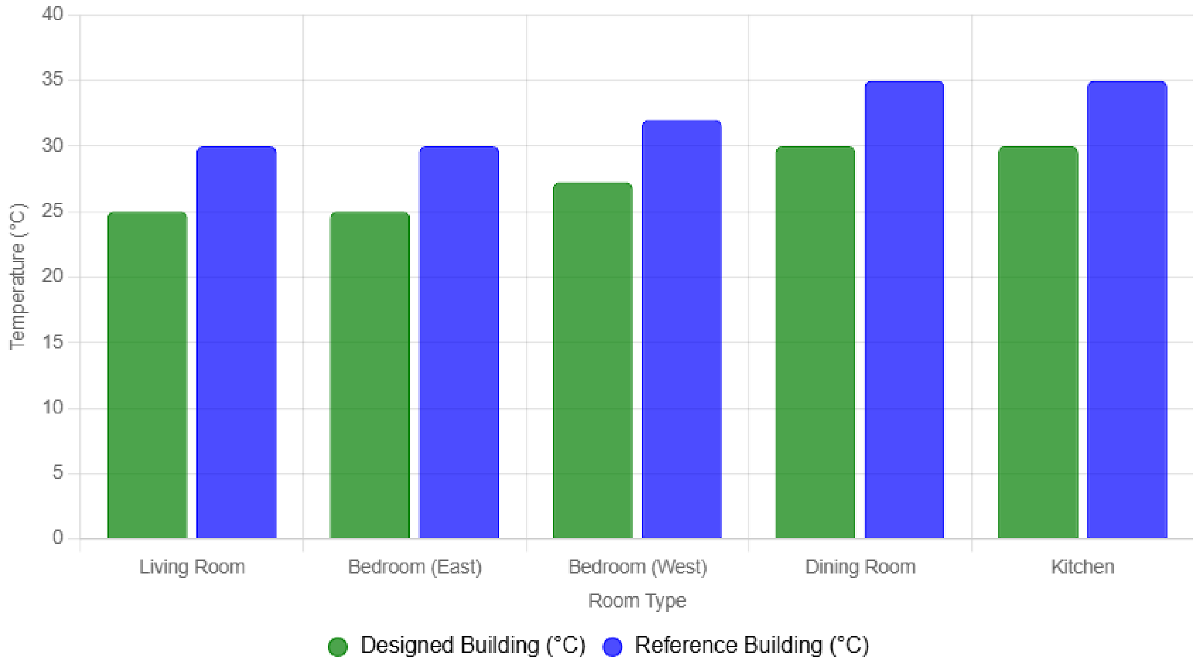


Figure A.3 Insulation Performance(Source: Annex A.3)

PART 05

Case Study: Haikou Binhai Jingyue

Project Overview

01 Location and Details

Haikou Binhai Jingyue is a 26- story residential building located in Qiongshan District, Haikou, Hainan. With a total area of 15,442 square meters, the project showcases various sustainable technologies and design features.

02 Sustainable Technologies Applied

The project incorporates a range of sustainable technologies, including passive strategies such as natural ventilation, green roofs, and shading, as well as active technologies like photovoltaics. Prefabrication techniques such as aluminum formwork and composite slabs are also employed to enhance sustainability.

Performance Outcomes

Energy Savings and Carbon Reduction

The application of the proposed design framework at Haikou Binhai Jingyue has resulted in significant energy savings of 10.79% and carbon reduction of 65.82%. These outcomes underscore the effectiveness of the sustainable design approach.

Thermal Comfort

The thermal comfort level at Haikou Binhai Jingyue is 54.77%, indicating a high level of indoor comfort for the occupants. This is a critical aspect of sustainable design, as it ensures that the building meets the needs and expectations of its users.

PART 06

Economic Analysis

Costs and Benefits

Initial Costs

The initial construction costs for the sustainable design elements at Haikou Binhai Jingyue range from 4,000 to 4,200 yuan per square meter, representing a 14.3% increase compared to traditional construction methods.

Key Technology Costs

The key technologies employed in the project, such as aluminum formwork and photovoltaics, contribute significantly to the overall sustainability and cost- effectiveness of the design.

Economic Viability

Annual Savings

The annual savings resulting from the sustainable design measures at Haikou Binhai Jingyue amount to 237,000 yuan. This represents a substantial economic benefit for the project.

Payback Period and NPV

The payback period for the initial investment in sustainable technologies is estimated to be between 5 and 8 years. Additionally, the Net Present Value (NPV) over a 50- year period is 23 million yuan, indicating the long- term economic viability of the design.

PART 07

Conclusions and Prospects

Conclusions

This study, with the tropical Marine climate of Hainan as the background, constructed a multi-standard design framework for building sustainability based on the integration and optimization of energy, materials and space efficiency, and explored the application paths of sustainable design in theory and practice. The study systematically analyzed key dimensions such as energy efficiency optimization, material recycling, spatial function integration, and climate-adaptive design through hierarchical design methods and passive low-energy technology, combined with PKPM simulation and BIM technology. In the case study of the 26-story residential project in Qiongshan District, Haikou City, the design scheme effectively reduced energy consumption (with an energy-saving rate of 10.79% for the envelope structure), reduced annual operating carbon emissions (with an optimised ratio of 65.82%), and improved indoor thermal comfort (PPD value controlled at 5.03%-12.28%). These figures collectively demonstrate the applicability and superiority of the design in Hainan's tropical climate, reaching the two-star standard of green buildings in Hainan Province (Annex 5-8). The technologies adopted in the project, such as green roofing,

Conclusions

photovoltaic integration, prefabricated construction and pipeline separation, not only achieve efficient resource utilization, but also significantly improve the building's microclimate through natural ventilation and shading design, verifying the feasibility and superiority of the multi-standard design framework in the tropical island environment.

The practical significance of this study lies in providing a scientific basis and practical model for the development of green buildings in Hainan. In the context of China's "dual carbon" goals and the construction of the Hainan International Free Trade Port, the research results provide technical support for reducing regional carbon footprints and promoting ecological civilization construction by optimizing resource efficiency throughout the entire life cycle of buildings. The combination of localized materials (such as volcanic stone, bamboo and wood) and traditional architectural wisdom (such as the ventilation structure of Li houseboats) used in the case with modern technology shows the path of the integration of regional culture and sustainable design. In addition, the study's economic analysis shows that although the initial cost of two-star green buildings increases by 8% to 15%, the cost can be recovered within 5 to 8 years through energy savings (about 25 yuan per square meter per year) and policy subsidies, demonstrating the long-term economic benefits of sustainable design. These results are not only applicable to Hainan, but also provide a reference for green building design in tropical island regions around the world.

THANK YOU

SUPERVISOR'S REVIEW

Thesis title: *Multicriteria design of modern multilayered envelopes in terms of sustainability*

Author: Xu Haina

Speciality: 192 – Civil Engineering and Construction

Supervisor: PhD, Associate Professor Yuriy Biks

The master's thesis of Xu Haina presents a complex and relevant investigation focused on improving the energy performance and sustainability of building envelopes in tropical climates, using Hainan province as a case study. The work is structured around a well-developed multicriteria framework that integrates energy efficiency, environmental adaptation, material sustainability, and architectural optimisation.

The thesis includes a high-quality theoretical review, an in-depth application of simulation tools (PKPM, BIM, SEDU), and a comprehensive case study of the Haikou Binhai Jingyue Residential Building. The student demonstrated a sufficient degree of independence, proper use of simulation software, and an ability to formulate practical design and policy conclusions based on calculated performance indicators (energy savings of 10.79%, carbon reduction by 65.82%, thermal comfort ratio of 54.77%).

However, several issues should be addressed:

1. **Formatting deficiencies:** Page numbers are inconsistently applied, and some tables/figures lack proper captions or cross-references in the text.
2. **Graphical consistency:** Fonts vary between sections, and the formatting of formulas is absent or too simplified.
3. **Economic section (Chapter 5):** While economic aspects are mentioned, deeper calculations of life-cycle costs, NPV, and detailed comparison with conventional construction would strengthen the argument.
4. **Visual materials and appendices:** Some figures could be made more transparent and integrated with more precise labels and references in the explanatory text.

Overall, the thesis aligns with the objectives of the educational program, presents scientific novelty, and demonstrates clear practical relevance. The thesis can be recommended for defence with a grade **"Excellent" (A)** and its author is awarded the qualification "Master of Civil Engineering" in the speciality 192 - "Construction and Civil Engineering".

Supervisor: PhD, Associate Professor **Yuriy BIKS**

OPPONENT'S REVIEW

Thesis title: *Multicriteria design of modern multilayered envelopes in terms of sustainability*

Author: Xu Haina

Opponent: PhD, Professor Ivan KOTS

Xu Haina's master's thesis addresses a highly relevant problem in sustainable construction. The author proposes an original multicriteria framework that combines passive and active design technologies with a simulation-based evaluation. A valuable contribution is the adaptation of the methodology to the climatic and policy context of Hainan, which is a unique challenge.

The literature review is broad and analytical. The methodological part is solid, employing modern tools for energy modeling, carbon footprint assessment, and building information modeling. The selected case study is appropriate and provides quantitative justification of the proposed solutions. The practical outcome aligns well with policy standards such as DBJ 46-064-2023.

Criticism and recommendations:

- **Structure and presentation**: Some chapters are too text-heavy and could be improved by summarizing content visually (e.g., flowcharts, performance dashboards).
- **Lack of technical detailing**: While the simulation tools are referenced, there is limited description of boundary conditions, input parameters, or software versions used.
- **Economic indicators**: The analysis of economic feasibility is underdeveloped; it lacks references to cost indices or local construction budgets.
- **References**: While the bibliography is extensive, formatting does not fully meet DSTU 8302:2015 standards.

Despite these drawbacks, the work demonstrates a high level of scientific maturity, interdisciplinary competence, and technical reasoning. The thesis should be admitted for defence, and its author, if the relevant defence attitude will be demonstrated, deserves a grade **"Excellent" (A)** and could be awarded the qualification "Master of Civil Engineering" in the speciality 192 - "Construction and Civil Engineering"

Opponent:
PhD, Professor **Ivan KOTS**