______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-optimised design of sustainable envelopes for suburb areas»

Assigned by: 2nd year student, group 2B-23m
Speciality 192 Construction and Civil Engineering
(Code and name of the Speciality)

Cuimei 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)_________
Studies direction 19___Architecture and _Construction _
(Code and name)
Specialty 192 Civil Engineering and Construction
(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 Cuimei
(Full name)

1. Master's qualification thesis topic «Multicriteria-optimised design of sustainable envelopes for suburb areas»
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: This study is based on open-source data and actual project data from the XA nearly zero-energy public building in Shenzhen's suburban area, combined with China's Green Building Evaluation Standard (GB/T 50378-2019) and tropical climate characteristics.
4. Content of the settlement and explanatory note (list of issues to be developed): In this research, Chapter 1, "Introduction," reflects the relevance of the topic, its purpose, scientific novelty, practical significance, research tasks, subjects, and main bodies. Chapter 2 introduces the evaluation methods of sustainable building design employed in this study. The main research sections consist of three chapters (Chapters 3 to 5). Chapter 3 focuses on the theoretical basis and literature review, summarizing the current state of knowledge in sustainable building envelopes and identifying gaps that this study aims to fill. Chapter 4 delves into the technical pathways and standards for sustainable architectural design, exploring the specific tools and criteria used to achieve optimized design solutions. Chapter 5 presents a case analysis of the XA project, examining how technologies such as optimized material thicknesses,

thermal performance enhancements, and cost control contribute to achieving a near-zero-energy building.
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 Cuimei

(Signature) (Surname and initials)

Master's thesis supervisor BIKS Yuriy

(signature) (Surname and initials)

ABSTRACT

Xu Cuimei. Multicriteria-optimised design of sustainable envelopes for suburb areas, Master's qualification thesis in the speciality 192 - "Civil Engineering and Construction", Educational Project- "Industrial and Civil Engineering". VNTU, 2025. 86 p.

In English. Bibliography: 37 titles; fig. 14; tabl. 14.

With the increasing global energy consumption and environmental issues, the construction industry, as a major consumer of energy and emitter of carbon, urgently needs to transition toward a sustainable development model Suburbs, as non-core areas of urban development, often emphasize strict compliance with energy-saving standards during the design phase of sustainable buildings, while neglecting factors such as carbon emissions and construction costs associated with the building process. This study focuses on projects constructed in accordance with the requirements of China's Green Building Evaluation Standards, particularly examining the design phase, and employs a multi-objective optimization approach to develop optimized design strategies by considering building thermal performance, carbon emissions, and construction cost as key optimization objectives.

Building upon a synthesis of relevant theoretical research, this study is based on the XA nearly zero-energy public building project located in the suburbs of Shenzhen. By collecting and analyzing various design parameters of the project, and integrating literature review, simulation analysis, performance testing, and field investigation methods, an optimization model is established based on building heat transfer theory and life cycle carbon footprint theory. The Matlab platform, equipped with the NSGA-II algorithm, is employed to optimize the thickness of building envelope materials.

This study provides both practical case support and theoretical guidance for the design of sustainable building envelopes in suburban areas, promoting the green and low-carbon development of the construction industry. Compared to traditional single-objective design approaches, the integrated performance optimization framework proposed in this study demonstrates unique advantages in achieving multi-objective balance, offering valuable reference for future similar projects.

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

Keywords: sustainable building; building envelope; multi-objective optimization; thermal performance; carbon emission; cost control

CONTENTS

INTRODUCTION

Actuality of theme. The theme of sustainable suburban envelope design is highly relevant due to the growing need for low-carbon and energy-efficient buildings in expanding peri-urban areas. Suburban regions often lack tailored architectural strategies despite unique environmental, economic, and regulatory contexts. China's dual-carbon policy further emphasises the necessity of carbon footprint in construction. Therefore, optimising the thermal, environmental, and financial aspects of building envelopes can make a significant contribution to national energy and climate goals.

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

The purpose of the research is to develop a simulation-based methodology for multi-criteria optimisation of suburban building envelopes. The main tasks include modelling performance indicators, implementing a multi-objective optimisation approach, and evaluating design alternatives based on lifecycle efficiency.

The following problems must be solved:

To analyse the current state of suburban envelope design in terms of sustainability.

- To simulate thermal performance, embodied carbon, and cost for envelope options.
- To apply a multi-objective optimization algorithm (NSGA-II) in MATLAB.
- To develop recommendations for energy-efficient and cost-effective envelope configurations.

Object of the study

Sustainable envelope design of suburban public buildings

Subject of the study

Multi-objective optimization of thermal performance, carbon emissions, and lifecycle cost of suburban building envelopes

Methods of research

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

Literature review – to analyse existing theoretical approaches to sustainable envelope design.

Simulation analysis – to model energy performance, using tools like MATLAB and NSGA-II.

Performance testing – to validate simulation outcomes by comparing with physical performance indicators.

Field investigation – to assess real-life conditions and user needs in suburban projects.

Scientific novelty of the obtained results

The study introduces a customised multi-objective optimisation framework tailored to suburban architecture, integrating thermal, environmental, and economic factors. Unlike traditional single-objective methods, this research combines theoretical modelling with practical simulation and testing, offering a robust methodological advancement in sustainable design.

Practical significance of the obtained results

The results provide clear design guidance for low-carbon, energy-efficient suburban buildings and inform policymakers with reliable quantitative data. Optimized designs yield up to 19.8% lower CO_2 emissions and noticeable cost reductions, supporting the transition to near-zero-energy buildings.

Personal contribution of the master's student

Conductance of the simulation modelling using MATLAB and NSGA-II, developed the optimisation framework, and analysed case study results for the XA project in Shenzhen's suburbs. She also prepared comparative visualisations of optimised and non-optimised designs.

Approbation of the results of the master's thesis

The main results of this work were presented at the thesis [37] in the electronic version on the website of VNTU in the international scientific and practical conference Research, Problems, Prospects (MN-2025) Xu Cuimei, Biks Yuriy. Sustainable lca-optimised envelopes for suburban buildings / Xu Cuimei, Biks Yuriy, // 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/25458/21052 (Last accessed 06.06.2025).

Publications [38]

Xu Cuimei. A Brief Discussion on Energy Conservation Issues in Construction Projects. *Protection Engineering*. 2017. Vol. 17. P. 266-267. (in Chinese).

CHAPTER 1 INTRODUCTION TO THE MULTICRITERION-OPTIMISED DESIGN OF SUSTAINABLE ENVELOPES

1.1 Research background

Buildings have a far-reaching impact on the environment during their construction and operation. In the construction phase, according to the "World Energy Outlook 2022" released by the International Energy Agency (IEA), global building energy consumption accounts for about 30% of the total global energy consumption[1]. Among this, the energy consumption of building material production and transportation accounts for approximately 15%, while the energy used for construction site machinery operation, temporary facility construction and dismantling takes up around 10%[2]. Furthermore, the construction process generates a substantial amount of construction waste. As reported in the "Global Tracking of Construction, Mining and Demolition Waste" by the United Nations Environment Programme (UNEP), about 300–500 tons of construction waste is produced for every 10,000 square meters of construction[3]. This waste not only occupies vast land resources—it is estimated that tens to hundreds of hectares of land are needed for every 10 million tons of construction waste—but also causes soil and water body pollution. Some waste components containing harmful substances, such as paints and preservatives, may enter groundwater through surface runoff, affecting water quality[4]. In addition, the construction phase also leads to significant carbon emissions. Data from the World Bank's "Global Carbon Budget" indicates that carbon emissions during the entire construction stage account for 20%–30% of the carbon emissions over the entire life cycle of a building[5].

During the operational phase, building energy consumption is mainly concentrated in heating, cooling, lighting and ventilation. Statistics from the IEA show that in the operational energy consumption of buildings, heating and cooling account for about 50%, lighting for approximately 20%, and ventilation for around 10%[1]. These energy consumptions not only result in the extensive use of energy but also produce a large amount of greenhouse gas emissions. The "Electricity Carbon Emission Coefficient Report" released by China National Grid shows that about 0.7–0.8 kilograms of carbon dioxide emissions are generated for every kilowatt-hour of electricity consumed[6]. The dense layout of buildings and their numerous hard surfaces also exacerbate the urban heat island effect. A report from the Chinese Academy of Sciences' Institute of Ecology and Environmental Sciences indicates that the temperature in city centers can be 2–5 degrees Celsius higher than that in surrounding suburban areas, affecting the urban ecological environment and the quality of life for residents[7]. To achieve harmony between buildings and nature, sustainable development has become an essential path for the future of the construction industry. Sustainable buildings aim to reduce negative environmental impacts while enhancing energy-utilisation efficiency and indoor environmental quality. Constructing sustainable buildings not only helps protect the environment but also improves residents' quality of life and promotes social sustainability.

To promote sustainable development in the construction sector, the Chinese government has introduced a series of policies at the national level. As early as 2008, the "Regulations on Energy Saving of Civil Buildings" were issued, mandating that new civil buildings must meet energy-saving standards and encouraging energy-saving retrofits for existing buildings. The regulations also stipulate requirements for the design, construction, acceptance and operation management of building energy saving[8]. In 2006, the Ministry of Housing and Urban-Rural Development of China released the first edition of the "Green Building Evaluation Standard," aimed at advancing green building development. The standard comprehensively evaluates buildings in terms of land saving, energy saving, water saving, material saving and indoor environmental quality, encouraging projects to use eco-friendly materials and energy-saving technologies[9]. During China's 14th Five-Year Plan period in 2021, the "14th Five-Year Plan for Building Energy Saving and Green Building Development" was released, clarifying the goals and tasks for building energy saving and green building development, including raising energy-saving standards for new buildings, promoting energy-saving retrofits for existing buildings and encouraging the application of renewable energy in construction[10]. Moreover, China has committed to the global "3060" dual-carbon target, aiming for carbon peak by 2030 and carbon neutrality by 2060, further highlighting its determination and responsibility in addressing climate change[11].

Under the impetus of these national policies, research institutions, renowned universities and leading enterprises in China have actively engaged in theoretical research, formulated a range of energy-saving and emission-reduction standards and developed various tools, effectively promoting the implementation and development of sustainable building design. As a vital component of buildings, envelopes significantly impact thermal performance, acoustic performance, lighting and the comfort and durability of the indoor environment. Therefore, design research and optimisation of sustainable building envelopes not only help improve energy-utilisation efficiency but also enhance indoor environmental quality, reduce negative environmental impacts and thus drive the sustainable development of the construction industry[12].

1.2 Current research status at home and abroad

1.2.1 Domestic research status

Significant progress has been made in the research of sustainable building design in China, covering various aspects such as building thermal performance, acoustics, optics, the full-life-cycle carbon footprint, durability and green buildings. The current research status in each area is as follows.

In terms of building thermal performance, domestic research primarily concentrates on enhancing the energy-efficiency of building envelopes across diverse climatic conditions. This includes exploring energy-saving technologies for walls, windows, and roofs. For example, in warm climates, studies have delved into the influence of building orientation, shape coefficient, window-to-wall area ratio, envelope thermal design, shading design, and natural ventilation design on building energy consumption and indoor thermal comfort. These investigations utilize climate analysis and passive design strategies. In regions characterized by hot summers and warm winters, research has employed the DeST-h energy simulation software to assess the thermal performance and energy consumption of residential buildings in three representative cities: Guangzhou, Nanning, and Haikou. Furthermore, the impact of envelope thermal parameters on building energy consumption has been examined. These studies offer a scientific foundation for building thermal design in various climate zones.

Regarding building acoustic performance, domestic research has primarily focused on the acoustic properties of porous materials and acoustic metamaterials. It has been found that the acoustic performance of porous materials is significantly influenced by their structure and material properties. Additionally, progress has been made in the research of acoustic metamaterials, particularly in the low-frequency sound-insulation performance of film-type and thin-plate-type acoustic metamaterials. These studies provide new ideas and methods for enhancing the sound-insulation effect of buildings. In terms of building acoustic-environment simulation and analysis, domestic software such as PKPM from the China Academy of Building Research and the green-building analysis software from

Tsinghua TH SWARE possess acoustic-analysis capabilities. PKPM-Sound is a software specifically designed for building acoustic-environment simulation and analysis. It features rapid modelling, noise-control and optimisation-design functions, powerful post-processing capabilities, a rich database of noise sources, efficient computation and reliable results. The TH SWARE Green Building Energy-saving Series software covers the simulation and analysis of "architecture both inside and outside, as well as wind, light, heat and sound," and applies BIM and the "one-model-multiple-calculations" technology to achieve improvements in both work efficiency and quality. Among them, the TH SWARE Building Acoustic Environment SEDU2025 module can perform outdoor site-environment noise analysis. By setting up noise sources, obstacles and surrounding buildings, it can calculate the noise in the building's surrounding environment and make compliance judgments, and it can also achieve relay calculations from outdoors to indoors[13].

In the area of building optical performance, domestic research has mainly focused on the optical and thermal properties of building glass. Studies have discussed the relationship between glass spectral data and its performance and have proposed the concept of the transmittance-to-shading ratio. Additionally, research has explored the heat-insulation and energy-saving performance of reflective/radiative coatings, including optical-performance testing, heat-transfer-model establishment and energy-saving-effect simulation. These studies help improve the natural-lighting efficiency of buildings, reduce the use of artificial lighting and lower building energy consumption[14].

Domestic research on the full-life-cycle carbon footprint of buildings is quite extensive. Studies have sorted out the sources of the full-life-cycle carbon footprint of buildings, from production and transportation, construction, operation and maintenance, demolition to the treatment of construction waste, and have summarised the latest research results on reducing carbon emissions, such as using alternative additives, improving design, re-utilising construction waste and water resources, etc. Moreover, some studies have constructed a green-building full-life-cycle carbon-emission calculation model based on BIM technology and have proposed the benchmark-management method. These studies provide references for the formulation of energy-saving and emission-reduction models and policies in the construction industry[15].

Regarding building durability, domestic research has mainly focused on the weatherability, waterproof performance, crack resistance, water-penetration resistance, ageing resistance and corrosion resistance of envelopes. It has been found that the durability of building materials is affected by various factors, including the properties of the materials themselves, environmental conditions and application situations. For example, changes in humidity and temperature can cause significant changes in the physical properties of materials. In high-humidity environments, materials are prone to water absorption and expansion, reducing their compressive strength, while extreme temperatures can cause materials to expand and contract thermally, resulting in cracks and damage. In coastal or highsalinity areas, chloride ions in the air have a strong corrosive effect on metal and concrete structures, accelerating material ageing. Moreover, construction techniques and the way materials are used can also significantly affect the durability of materials. By optimising material ratios, strengthening protective measures, using composite materials and new additives, etc., the durability and environmental adaptability of building materials can be effectively improved[16].

In the field of green buildings, domestic research is quite in-depth. Studies have proposed using a combination of environmental-system design and local culture to design sustainable buildings with Chinese regional characteristics. Additionally, some research has explored the carbon-emission accounting methods and reduction pathways for the full life cycle of green buildings. These studies provide theoretical support and technical guidance for green-building design and implementation[17].

1.2.2 International research status

In developed countries abroad, sustainable development in the construction industry has become a research hotspot in both academia and industry. Many countries have conducted extensive and in-depth research on sustainable building envelopes and have achieved a series of important results.

European countries are at the forefront of research on sustainable building envelopes, especially in the field of building energy saving and environmental protection. Research institutions and universities in Germany, Denmark and

Sweden have made significant progress in high-performance insulation materials, energy-saving window systems and building-integrated renewable-energy technologies.

Germany's Passivhaus (passive house) standard is a benchmark in the global building-energy-saving field. Passive houses achieve extremely low energy-consumption levels through efficient thermal insulation, airtightness and heat-recovery ventilation systems. German research institutions and enterprises continuously develop new insulation materials and energy-saving technologies, such as vacuum insulation panels (VIPs) and high-performance triple-glazed windows with two cavities, significantly improving the thermal performance of buildings. In addition, Germany pays attention to the durability and indoor environmental quality of building envelopes, ensuring the long-term performance of buildings through strict building standards and certification systems [18].

Denmark has rich experience in building energy saving and renewable-energy application. The Technical University of Denmark and research institutions have developed a variety of intelligent building-envelope systems that can automatically adjust the thermal performance of buildings according to indoor and outdoor environmental conditions. For example, smart windows and dynamic insulation materials can automatically adjust light transmittance and thermal-insulation performance according to solar radiation and temperature changes, effectively reducing building energy consumption. Denmark also actively promotes the application of building-integrated solar photovoltaic systems

(BIPV). By integrating solar photovoltaic panels into building envelopes, it achieves energy self-sufficiency for buildings [19].

Sweden has conducted a great deal of research on the durability and indoor environmental quality of building envelopes. Swedish research institutions have developed a variety of new building materials and construction techniques, such as self-healing concrete and airtight construction processes, significantly improving the durability and airtightness of building envelopes. Moreover, Sweden pays attention to the acoustic performance and indoor environmental quality of building envelopes, ensuring that buildings provide a comfortable indoor environment while saving energy through optimised design and material selection [20].

The United States has also made significant progress in the research of sustainable building envelopes, especially in building simulation analysis and performance optimisation. The U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) and other institutions have developed a variety of advanced building simulation tools and design guidelines to help architects and engineers optimise the performance of building envelopes.

In terms of building simulation analysis, the U.S. has developed a variety of building simulation software, such as EnergyPlus, DOE-2 and TRNSYS, which can accurately simulate the energy consumption, thermal comfort and indoor environmental quality of buildings. These tools can help designers evaluate the performance of different envelope options in the design stage, optimise design parameters and achieve building energy-saving goals. Moreover, U.S. research institutions and enterprises have developed a variety of high-performance building materials, such as phase-change materials (PCMs) and aerogel insulation materials. PCMs can absorb and release latent heat, effectively regulating indoor temperature and reducing the heating and cooling demands of buildings. Aerogel insulation materials have an extremely low thermal conductivity, which can significantly improve the thermal-insulation performance of building envelopes. In the research on the comprehensive performance of sustainable buildings, the U.S. has launched the Leadership in Energy and Environmental Design (LEED) certification system, which has a wide influence globally. LEED certification assesses the sustainable performance of buildings from multiple aspects, including the thermal performance of envelopes, material selection and indoor environmental quality. Buildings that have obtained LEED certification must meet strict sustainability standards in the design and construction process, promoting the sustainable development of the construction industry [21].

Australia has also made significant progress in the research of sustainable building envelopes, especially in adapting to local climate conditions and renewable-energy application. Australian research institutions and universities have developed a variety of climate-adaptive building-envelope design methods that can effectively cope with the hot and dry or hot and humid climate conditions of the region. For example, by optimising building orientation, shading design and natural ventilation systems, the solar radiation heat gain and cooling demand of buildings are reduced. In terms of renewable-energy application, Australia actively promotes the application of solar and wind energy in buildings. By integrating solar photovoltaic panels and wind turbines into building envelopes, it achieves energy self-sufficiency for buildings. Moreover, Australia has developed a variety of intelligent building systems that can automatically adjust the energy consumption and indoor environmental quality of buildings according to indoor and outdoor environmental conditions [22].

Japan has also made significant progress in the research of sustainable building envelopes, especially in the application of new materials and technologies. In the research and application of smart materials and nanomaterials, Japanese research institutions and enterprises have developed a variety of smart materials and nanomaterials, such as shape-memory alloys and nano-insulation materials. These materials can automatically adjust the thermal performance of buildings according to environmental conditions, significantly improving the energy-saving effect of buildings. In the research and application of building-integrated renewable energy, Japan actively promotes the application of solar photovoltaic panels and wind turbines in buildings. By integrating these renewable-energy devices into building envelopes, it achieves energy self-sufficiency for buildings. Moreover, Japan has developed a variety of intelligent building systems that can automatically adjust the energy consumption and indoor environmental quality of buildings according to indoor and outdoor environmental conditions [23].

Overall, international research on sustainable building envelopes covers multiple aspects such as thermal performance, acoustic performance, durability, carbon emissions and economic performance. These research results provide important references and support for the sustainable development of the global construction industry.

1.3 Research methods and technical routes

1.3.1 Research methods

(1) Literature review method

The literature review method involves extensively consulting and systematically organising relevant literature from both domestic and international sources to acquire the theoretical foundations and the latest research findings in the field of sustainable building envelopes. The specific steps include consulting academic databases, journal papers, professional books, government reports, and industry standards from China and abroad. Literature related to building thermal performance, acoustic performance, optical performance, full - life - cycle carbon footprint, and durability is collected and systematically organised and analysed. The collected literature is systematically organised, and the background, purpose, methods, and conclusions of different studies are analysed to identify current research hotspots, difficulties, and trends. Based on this, a literature review is written to summarise the research findings and shortcomings of domestic and international studies, clarify the innovation points and research directions of this study.

(2) Simulation analysis method

The simulation analysis method utilises advanced building simulation software to simulate and optimise the performance of building envelopes. The specific steps include selecting simulation software, such as PKPM and TH SWARE, which are localised building simulation software in China. These software programs can precisely simulate the energy consumption, thermal comfort, and indoor environmental quality of buildings. A detailed building envelope simulation model is established based on the project overview and design parameters, including the building's geometric shape, material properties, and boundary conditions. Multiple simulation scenarios are designed, each corresponding to different envelope parameters and design values, to evaluate the performance of each scenario in terms of energy consumption, thermal comfort, and indoor environmental quality. The simulation results are analysed in detail to identify the advantages and disadvantages of each scenario. The design parameters of the envelope are optimised based on the analysis results to improve the building's energy - utilisation efficiency and indoor environmental quality.

(3) Performance - testing analysis method

The performance - testing analysis method involves on - site testing of the performance of building envelopes to verify the accuracy and reliability of the simulation analysis results. The specific steps include formulating a test plan based on the research objectives and characteristics of the envelope. The plan includes details such as the test items, methods, equipment, and schedule. High - precision testing equipment, such as heat - flux meters, temperature sensors, and sound - level meters, is selected to ensure the accuracy and reliability of the test data. On - site testing is carried out during the construction and operation of the building according to the test plan. The testing content includes the thermal performance, acoustic performance, optical performance, and durability of the envelope. The test data are organised and analysed to evaluate the actual performance of the envelope. By comparing the test results with the simulation results and design objectives, existing problems and shortcomings are identified to provide a basis for subsequent optimisation and design.

(4) Field - research method

The field - research method involves on - site investigations and interviews to understand the actual application of building envelopes in suburban areas and user needs. The specific steps include selecting research objects, such as representative suburban building projects, including both existing sustainable buildings and traditional buildings, covering different building types, scales, and functions. A detailed research questionnaire is designed based on the research objectives and content, including basic building information, envelope design and construction, energy consumption, and indoor environmental quality. On - site interviews are conducted with building designers, constructors, and users to gain insights into their experiences and opinions on envelope design, construction, and use. Data from the questionnaires and interview records are collected, organised, and analysed. By comparing the actual situations of different building projects, the advantages and shortcomings of sustainable building envelopes in practical applications are summarised to provide practical references for this study.

1.3.2 Technical route

After comprehensively integrating various research methods and technical approaches, this study has established a systematic technical route to ensure the scientific rigor, comprehensiveness, and feasibility of the research. The technical route diagram is shown in Figure 1.1.

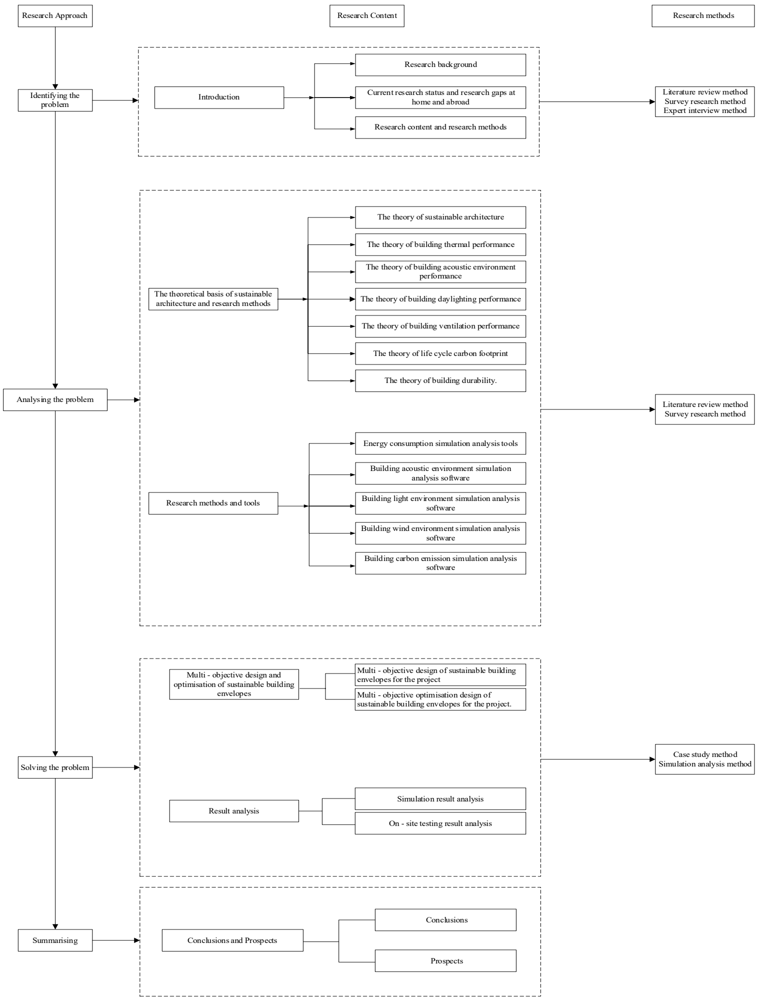

Figure 1.1 – Technical route diagram of the project study

1.4 Research significance

This research focuses on the multi-objective optimization design of sustainable building envelopes in suburban areas, holding significant theoretical and practical implications.

1.4.1 Theoretical significance

Enriching the theoretical system of sustainable building

Through an in-depth investigation into the multi-objective optimization design of suburban building envelopes, this study refines the theoretical framework for envelope design in sustainable architecture, providing comprehensive and systematic support for constructing a robust sustainable building theory. By integrating multi-objective optimization (e.g., balancing thermal performance, carbon emissions, and cost efficiency), this work explores scientifically grounded design principles and methodologies, advancing sustainable building theory in both depth and breadth.

Expanding building envelope design theory

Introducing multi-objective optimization into suburban building envelope design overcomes the limitations of traditional single-objective approaches. By holistically optimizing thermal performance, carbon emissions, and lifecycle costs, this research proposes innovative strategies that enrich the theoretical foundation of envelope design, fostering the development of a more integrated and systematic theoretical framework.

Advancing building performance simulation and evaluation theory

The application of diverse building simulation methods (e.g., energy modeling, daylight analysis) and performance evaluation metrics (e.g., carbon footprint assessment, cost-benefit analysis) enhances the accuracy and reliability of envelope performance assessments. This progress drives the evolution of building performance simulation theory, offering scientifically robust decision-making tools for envelope optimization.

1.4.2 Practical significance

Promoting sustainable development in suburban architecture

Suburban areas, as transitional zones between urban and rural regions, face unique architectural challenges. This study provides practical technical guidance for designing energy-efficient, low-carbon suburban building envelopes. Optimized designs improve energy utilization efficiency, reduce carbon emissions, and enhance indoor environmental quality, fostering harmony between suburban development and ecological sustainability.

Enhancing energy efficiency and economic performance

The multi-objective optimization framework minimizes energy consumption while maintaining functional and comfort requirements. By improving the insulation performance of building envelopes, energy demands for heating, cooling, and lighting are significantly reduced, lowering operational costs. Strategic material selection further decreases construction and maintenance expenses, enhancing overall economic viability.

Improving Indoor Environmental Quality and Occupant Comfort

Optimized envelope designs prioritize thermal stability, noise reduction, and daylight utilization. Enhanced thermal performance ensures consistent indoor temperatures, while effective noise insulation and natural lighting reduce reliance on artificial systems, mitigating visual fatigue and improving occupant health, productivity, and comfort.

Driving Technological Innovation and Industrial Upgrading

This research introduces innovative design philosophies and technical methodologies for building envelopes, stimulating technological advancements in the construction industry. Widespread adoption of these approaches accelerates the sector's transition toward energy-efficient, eco-friendly, and sustainable practices, enhancing global competitiveness and fostering industrial transformation.

Informing Policy Development for Sustainable Construction

The findings provide evidence-based insights for policymakers to formulate regulations on energy conservation, carbon reduction, and sustainable development. By offering technical data and quantitative references, this study supports the creation of targeted policies to steer the construction industry toward socio-economic and environmental sustainability.

1.5 Innovations

Innovation 1: integrated multi-method research strategy

This study innovatively combines literature review, simulation analysis, performance testing, and field investigation into a cohesive research framework. The literature review systematically synthesizes global research findings to establish a theoretical foundation. Simulation analysis enables precise modeling and optimization of building envelope performance, enhancing scientific rigor and design rationality. Performance testing validates simulation accuracy and reliability, ensuring practical applicability. Field investigations capture real-world application scenarios and user needs in suburban contexts, ensuring targeted and actionable outcomes. This multi-method integration elevates the study's comprehensiveness and depth, offering novel methodologies for sustainable envelope design research.

Innovation 2: suburban-specific customized design

Unlike conventional urban or rural building studies, this research focuses on multi-objective optimization of suburban building envelopes, tailored to unique geographical conditions, climatic characteristics, and user demands. It incorporates suburban-specific factors such as sunlight exposure, wind patterns, temperature-humidity profiles, as well as functional requirements, structural forms, and material availability. For example, the thermal, acoustic, and optical performance of walls, windows, and roofs in small-scale suburban public buildings is optimized to improve energy efficiency and indoor environmental quality. This suburban-centric approach addresses a critical gap in sustainable design research for transitional zones, delivering actionable solutions for suburban architectural sustainability.

Innovation 3: comprehensive performance optimization framework

A groundbreaking multi-objective optimization framework is established, integrating thermal performance, carbon emissions, and lifecycle costs into envelope design. Unlike traditional single-objective optimization, this framework employs multi-objective algorithms to synergistically optimize envelope parameters, balancing energy efficiency, indoor environmental quality, and environmental impact. For instance, when selecting wall insulation materials, both thermal insulation capability and embodied carbon are prioritized. This holistic framework provides a systematic and scalable model for enhancing the overall sustainability and performance of building envelopes.

Conclusions to Chapter 1

This chapter establishes the research context, highlighting the construction industry's urgent need for sustainable transformation as a major energy consumer and carbon emitter. Focusing on suburban areas often overlooked in sustainable design, the study employs multi-objective optimization (thermal performance, carbon emissions, cost) for building envelopes compliant with China's Green Building Evaluation Standards. The literature review reveals global research gaps, while the methodology combines theoretical analysis with practical approaches including simulation and field investigation. The research contributes both theoretically (enriching sustainable design frameworks) and practically (advancing green suburban development).

CHAPTER 2 FUNDAMENTALS AND METHODS OF SUSTAINABLE DESIGN

2.1 Fundamental theories

2.1.1 Building thermal science theory

Building thermal science is a discipline that studies the heat exchange processes between buildings and their surrounding environments, as well as their impacts on building energy consumption and indoor thermal comfort. It primarily focuses on the laws of heat transfer between buildings and the external environment, including three basic heat transfer modes: conduction, convection, and radiation [24].

Heat conduction refers to the process of heat transfer through a material from a high-temperature region to a low-temperature region. In building envelopes, heat conduction mainly occurs in components such as walls, roofs, and floors [25]. During winter, when outdoor temperatures are low, indoor heat is conducted outward through walls, leading to a drop in indoor temperature. The rate of heat conduction depends on factors such as the material's thermal conductivity, thickness, and temperature difference. Materials with lower thermal conductivity exhibit better insulation performance, slowing heat transfer. For example, expanded polystyrene foam boards, which have low thermal conductivity, are commonly used for exterior wall insulation.

Heat convection refers to the macroscopic movement of fluids (such as air or water) driven by temperature differences, resulting in heat transfer. Within buildings, heat convection primarily manifests as natural air convection [26]. In winter, air near indoor radiators heats up and rises, while cooler air moves in to replace it, creating air circulation that gradually raises indoor temperatures. The intensity of heat convection is influenced by temperature differences, air velocity, and the physical properties of the air. In architectural design, natural convection between indoor and outdoor air can be promoted by strategically positioning windows and doors, improving indoor ventilation and reducing air conditioning energy consumption.

Heat radiation refers to the process of heat transfer through electromagnetic waves. In buildings, solar radiation is one of the most significant factors affecting thermal performance [27]. Solar radiation enters interiors through windows, raising indoor temperatures. Simultaneously, building envelopes also radiate heat outward. In summer, roofs absorb solar radiation and emit heat inward, increasing indoor temperatures. The intensity of heat radiation depends on factors such as surface temperature, material properties, and the angle of radiation. In architectural design, measures such as shading devices and low-emissivity glass can be employed to mitigate the impact of solar radiation on indoor thermal environments.

Building thermal science theory holds great significance in sustainable architectural design. By rationally designing the thermal performance of building envelopes, energy consumption can be effectively reduced, and indoor thermal comfort improved [28]. The use of high-performance insulation materials and thermal barriers can minimize heat loss during heating and cooling processes, lowering energy usage. Meanwhile, optimizing building orientation and layout, along with leveraging natural ventilation and shading techniques, can enhance indoor thermal environments and residents' quality of life. Additionally, building thermal science theory provides a scientific basis for evaluating and optimizing the thermal performance of buildings, promoting sustainable development in the construction industry.

2.1.2 Life cycle carbon footprint theory

The Life Cycle Assessment (LCA) theory is a scientific method for evaluating greenhouse gas emissions across the entire life cycle of a product, service, or system—from raw material extraction and production to use and final disposal. In the field of architecture, the LCA theory is used to quantify carbon emissions at each stage of a building’s life cycle, providing a scientific basis for sustainable design, construction, and operation [29].

The life cycle of a building consists of four main phases: raw material production, construction, operation and maintenance, and demolition and disposal. During the raw material production phase, the manufacturing of building materials generates significant carbon emissions, such as limestone decomposition and fuel combustion in cement production. In the construction phase, activities like equipment operation, material transportation, and on-site construction also contribute to carbon emissions. During the operation phase, energy consumption (e.g., heating, cooling, lighting, and hot water supply) is the primary source of carbon emissions. In the demolition and disposal phase, building dismantling and waste processing also produce a certain amount of carbon emissions.

The LCA theory quantifies carbon emissions at each stage by establishing a Life Cycle Inventory (LCI), which includes energy consumption and material flows in processes such as raw material extraction and processing, manufacturing and transportation, product use and maintenance, and disposal and treatment. By collecting and analyzing this data, the total carbon emissions of a building throughout its life cycle can be calculated.

The application of LCA theory in sustainable building design is highly significant. By assessing carbon emissions at different stages, designers can implement measures to reduce a building’s carbon footprint. In material selection, low-carbon materials such as recycled or locally sourced materials can be prioritized. In architectural design, optimizing building orientation, layout, and envelope performance can improve energy efficiency. During the operation phase, energy-efficient equipment and technologies—such as high-efficiency HVAC systems and lighting—can minimize energy consumption. Additionally, LCA theory can be used to evaluate the environmental impact of different design schemes, supporting decision-making in sustainable building design.

In summary, the Life Cycle Carbon Footprint Theory provides a comprehensive and systematic framework for assessing building sustainability. By applying LCA theory, carbon emissions throughout a building’s life cycle can be effectively reduced, contributing to the achievement of sustainable development goals in architecture.

2.2 Sustainable building envelope design evaluation methods

2.2.1 Building simulation analysis method

The building simulation analysis method is a computational approach that utilizes specialized software to model and analyze building performance, aiming to predict how a building will behave under various conditions and provide a scientific basis for design optimization. In sustainable building envelope design, this method is widely applied to assess thermal performance, acoustic performance, optical performance, and energy efficiency of building envelopes.

The principle of building simulation analysis involves creating a virtual model of a building and simulating physical processes—such as heat transfer, airflow, sound propagation, and light diffusion—under different climatic conditions, usage patterns, and maintenance scenarios. Simulation software typically relies on fundamental principles of building physics, including heat conduction, convection, radiation, as well as acoustic and optical propagation laws. By employing numerical computation methods to solve relevant physical equations, the software generates performance indicators for the building under various conditions.

The application of building simulation analysis in sustainable envelope design is highly significant. First, it enables performance prediction and comparison of different envelope design alternatives during the planning phase, assisting designers in selecting the optimal solution. For example, by simulating the insulation performance of various wall materials and constructions, designers can choose the most suitable wall system for local climate conditions, thereby reducing heating and cooling demands. Second, this method can evaluate the performance evolution of building envelopes over different usage phases, providing guidance for maintenance and retrofitting. By simulating long-term energy consumption trends, potential performance degradation in the envelope can be identified early, allowing for timely maintenance measures to extend the building's service life. Finally, building simulation analysis also supports energy management and operational optimization. By modeling energy consumption patterns, effective energy management strategies can be formulated to enhance efficiency and reduce operational costs.

In summary, building simulation analysis is an indispensable tool in sustainable building envelope design. By simulating building performance under various conditions, it provides a scientific foundation for design, maintenance, and operation, contributing to improved sustainability and harmonious coexistence between buildings and the environment.

2.2.2 Artificial neural network-based building performance prediction methods

With the rapid development of computer technology and artificial intelligence, Artificial Neural Network (ANN)-based building performance prediction methods have been widely adopted in sustainable building design. ANNs are mathematical models that simulate the structure and function of biological neurons, featuring strong nonlinear mapping capabilities and adaptive learning abilities, enabling efficient processing and prediction of complex building performance data[30].

(1) Fundamental principles of artificial neural networks

An ANN consists of numerous interconnected neurons (nodes) arranged in a specific topological structure to form a complex network. Each neuron receives input signals from others, processes them through weighted summation and activation functions, and transmits output signals to subsequent neurons. By adjusting connection weights and biases, the network continuously learns and optimizes its outputs to approximate actual building performance data.

Common ANN architectures include Multilayer Perceptron (MLP), Convolutional Neural Network (CNN), and Recurrent Neural Network (RNN). For building performance prediction, MLP is the most frequently used structure, comprising an input layer, hidden layers, and an output layer, trained and optimized via forward and backward propagation algorithms.

(2) Steps for ANN-based building performance prediction

Data collection and preprocessing:Gather building-related data such as geometric parameters, material properties, weather conditions, and energy consumption. Clean, normalize, and extract features to prepare inputs for the ANN.

ANN model construction:Select an appropriate network architecture (e.g., neuron count, layers, activation functions) and initialize the model based on prediction requirements.

Model training:Split data into training, validation, and test sets. Train the model using the training set, adjusting weights and biases via backpropagation to minimize output deviations. The validation set fine-tunes the model to prevent overfitting.

Model testing and evaluation:Assess the trained model's accuracy and generalization using the test set. Common metrics include Mean Squared Error (MSE), Mean Absolute Error (MAE), and R-squared.

Performance prediction and optimization:Deploy the trained model to predict performance for new designs or operational scenarios, guiding decisions. Optimize envelope parameters or energy systems based on predictions to enhance sustainability.

(3) Advantages of ANN-based prediction methods

Strong nonlinear modeling: Capable of capturing complex nonlinear patterns in building performance data for accurate predictions.

Adaptive learning: Automatically adjusts parameters to suit diverse prediction tasks and data characteristics.

High-Efficiency data processing: Handles large datasets rapidly, enabling timely design and operational support.

Generalization: Well-trained models reliably predict unseen data, aiding sustainable design and operation.

Practical applications

ANN methods are extensively used in real-world projects. For instance, in building energy retrofit projects, ANNs predict post-renovation energy consumption by analyzing historical energy data, envelope parameters, and equipment performance. These predictions quantify potential energy savings, validating retrofit measures before implementation.

In summary, ANN-based building performance prediction offers an efficient and precise tool for sustainable envelope design. By leveraging ANNs' modeling and learning capabilities, it provides scientific insights to advance sustainable practices in the construction industry.

Conclusions to Chapter 2

The chapter presents the theoretical pillars for sustainable envelope design: (1) Building Thermal Science (conduction, convection, radiation principles governing heat transfer), and (2) Life Cycle Assessment (carbon footprint evaluation across material production, construction, operation, and demolition phases). Two key evaluation methods are detailed: Building Simulation Analysis (performance prediction via software modeling) and Artificial Neural Networks (data-driven performance forecasting). These foundations enable systematic optimization of envelope systems while balancing energy efficiency, environmental impact, and economic viability.

CHAPTER 3 SUSTAINABLE BUILDING ENVELOPE DESIGN IN SUBURBAN AREAS

This chapter presents the XA Project in Shenzhen's suburban area as a case study, demonstrating how optimized envelope material selection can achieve optimal lifecycle energy consumption and cost while maintaining satisfactory indoor lighting conditions.

3.1 Project overview

The XA Project, located in the suburban Bao'an District of Shenzhen, is a near-zero energy consumption (nZEB) public building demonstration initiative. It aims to enhance local service infrastructure by providing visitors and residents with convenient, comfortable amenities while advancing green building development. The project aligns with China's "Dual Carbon" strategy and supports high-quality, sustainable growth.

With a total floor area of 1,276 m^2, the facility includes functional zones such as information services, lounges, dining areas, retail spaces, and offices. Its design adheres to nZEB principles, functionality, aesthetics, and safety, integrating energy-saving technologies and renewable energy systems—including solar PV, self-shading structures, daylighting, and natural ventilation—to significantly reduce operational energy use. The project complies with China's Assessment Standard for Green Building (GB/T 50378-2019) at the Two-Star certification level.

Upon completion, the XA Project will offer comprehensive tourist services, comfortable rest and dining environments, and a platform to promote local specialty products, thereby boosting regional economic development.

Beyond its functional role, the project serves as a pioneering model for Shenzhen's green building sector. Throughout construction and operation, emphasis has been placed on eco-friendly materials and energy-efficient systems to minimize environmental impact, embodying the principles of green architecture and sustainable development goals. The project design rendering is shown in Figure 3.1.

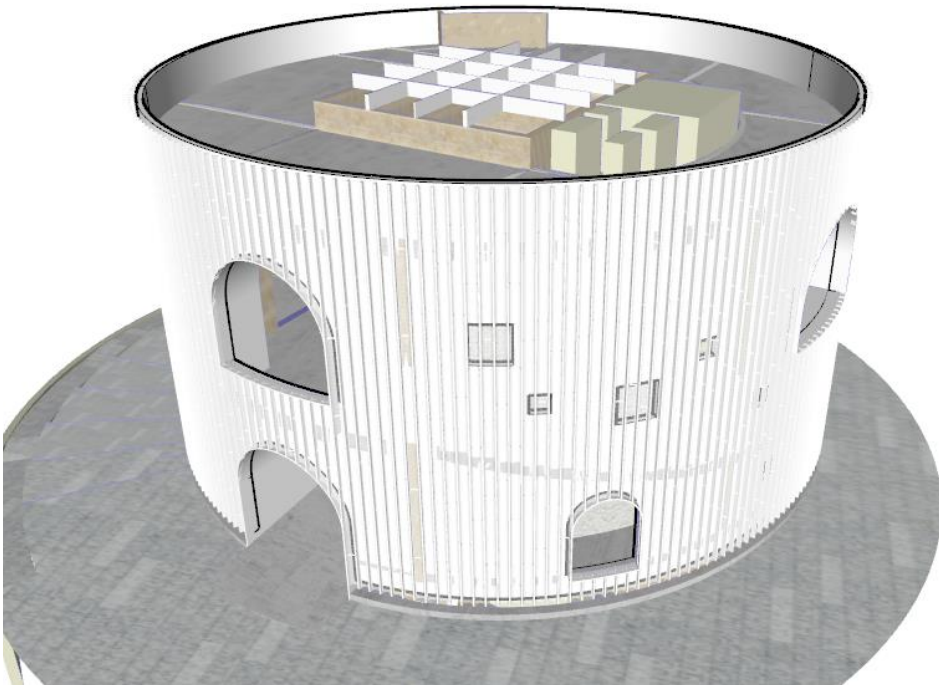

Figure 3.1 – Rendering of XA project

3.2 Project design

3.2.1 Design basis

This study conducts an optimized design focusing on three aspects of the building envelope: thermal performance, carbon emissions, and cost. The design strictly complies with relevant national and local standards and codes.

Thermal performance design

The thermal performance design primarily references the following Chinese national standards:

-Design Standard for Energy Efficiency of Public Buildings (GB 50189-2015)

-Thermal Design Code for Civil Buildings (GB 50176-2016)

-Considering the climatic characteristics of Shenzhen, Guangdong Province, the design also adheres to:

-Design Standard for Energy Efficiency of Public Buildings (SJG 44-2025)

-Assessment Standard for Green Building (GB/T 50378-2019), meeting the Two-Star certification requirements.

Carbon emission calculation

The carbon emission calculations are based on:

-Standard for Building Carbon Emission Calculation (GB/T 51366-2019)

-Standard for Carbon Emission Calculation of Building Decoration in Shenzhen (T/SZZS01 001-2021)

-China's building material carbon emission factors to ensure calculation accuracy.

Cost analysis

The material unit prices for the building envelope are determined according to:

National and Shenzhen construction cost calculation systems, including:

-Composition of Construction and Installation Engineering Costs (Jian Biao [2013] No. 44)

-Shenzhen Construction and Installation Engineering Cost Quota (2018 Edition)

-Shenzhen Construction Engineering Cost Management Regulations (Shenzhen Municipal Government Order No. 241)

These standards provide a scientific basis for subsequent cost analysis. The design references are summarized in the table 3.1.

Table 3.1 – Design basis

Design aspect	**Reference standards**
Thermal Performance	Design Standard for Energy Efficiency of Public Buildings (GB 50189-2015), Thermal Design Code for Civil Buildings (GB 50176-2016), Guangdong Implementation Rules for Design Standard for Energy Efficiency of Public Buildings (DBJ15-51-2007) Assessment Standard for Green Building (GB/T 50378-2019)
Carbon Emissions	Standard for Building Carbon Emission Calculation (GB/T 51366-2019) Standard for Carbon Emission Calculation of Building Decoration in Shenzhen (T/SZZS01 001-2021) China's building material carbon emission factors
Design aspect	Reference standards
Cost	Composition of Construction and Installation Engineering Costs (Jian Biao [2013] No. 44) Shenzhen Construction and Installation Engineering Cost Quota (2018 Edition) Shenzhen Construction Engineering Cost Management Regulations (Shenzhen Municipal Government Order No. 241)

This structured approach ensures compliance with regulatory requirements while optimizing the building envelope's performance, sustainability, and cost-effectiveness.

3.2.2 Climatic conditions of the project location

The project is located in the Shenzhen area, which is situated in southern China and enjoys a subtropical maritime climate characterized by warm and humid conditions throughout the year with abundant rainfall. Due to its proximity to the Tropic of Cancer, Shenzhen's climate features long summers without winter, with spring and autumn connected, offering a mild and pleasant climate. The annual average temperature is approximately 22.4 degrees Celsius, with the highest temperature reaching up to 36.6 degrees Celsius and the lowest around 1.4 degrees Celsius. Additionally, Shenzhen's climate is influenced by monsoons; southeasterly winds prevail in summer, while northerly winds dominate in winter. This change in wind direction plays a significant role in regulating the local climate. Given Shenzhen's coastal location, its maritime climate characteristics are evident. While summers are hot, sea breezes help alleviate some of the heat, making high temperatures more bearable. Winters are as warm as spring, with cold weather being relatively rare. Figure 3. 2 illustrates Shenzhen's climatic data, including wind frequency, average temperature, average relative humidity, and average precipitation, providing crucial climatic references for the design of the building envelope in this project.

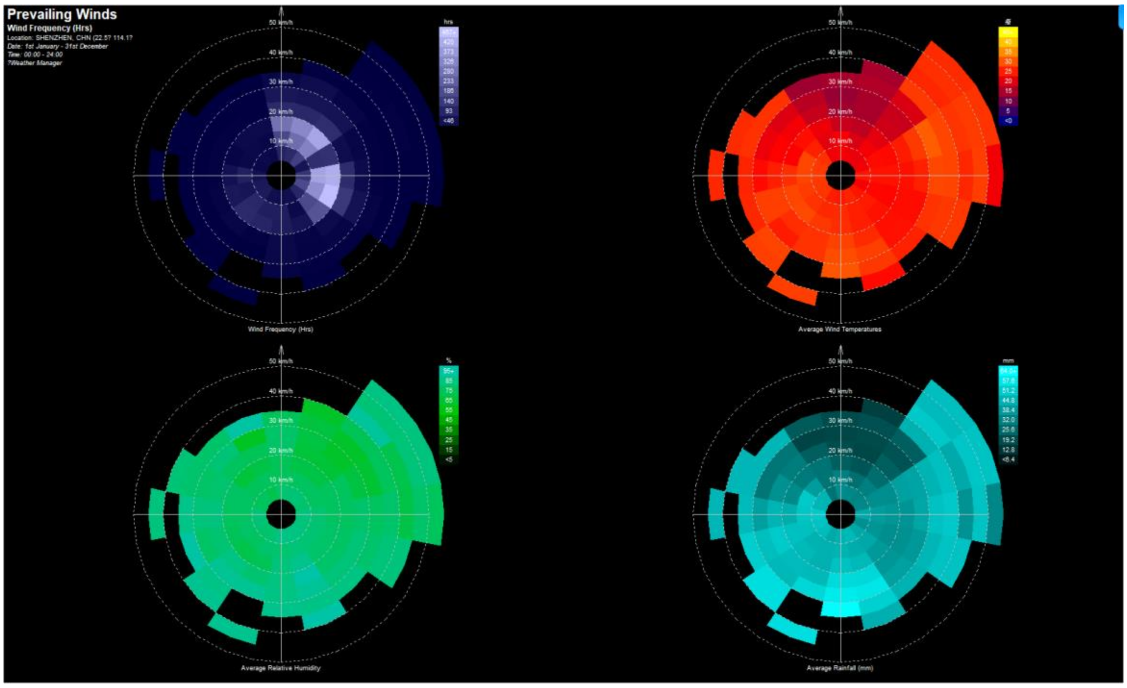

Figure 3.2 – Wind Frequency|Average Wind Temperatures|Average Relative Humidity|Average Rainfall

3.2.3 Floor plan design

The XA project adopts a circular structure in its plan design. A circular structure minimises the building's shape coefficient to the greatest extent, thereby reducing the insulation surface area and achieving optimal energy efficiency. Compared to buildings of other shapes, circular structures have a smaller ratio of surface area to volume, allowing the building to retain indoor heat more effectively during winter and reduce heat loss. In summer, this form also effectively reduces the absorption of solar radiation, lowering the cooling load on air conditioning systems. This design not only enhances the building's thermal performance but also significantly reduces energy consumption, aligning with the principles of sustainable architecture. The floor plans for Levels 1, 2, 3, and the roof are shown in Figures 3.3, 3.4, 3.5, 3.6, and 3.7, respectively.

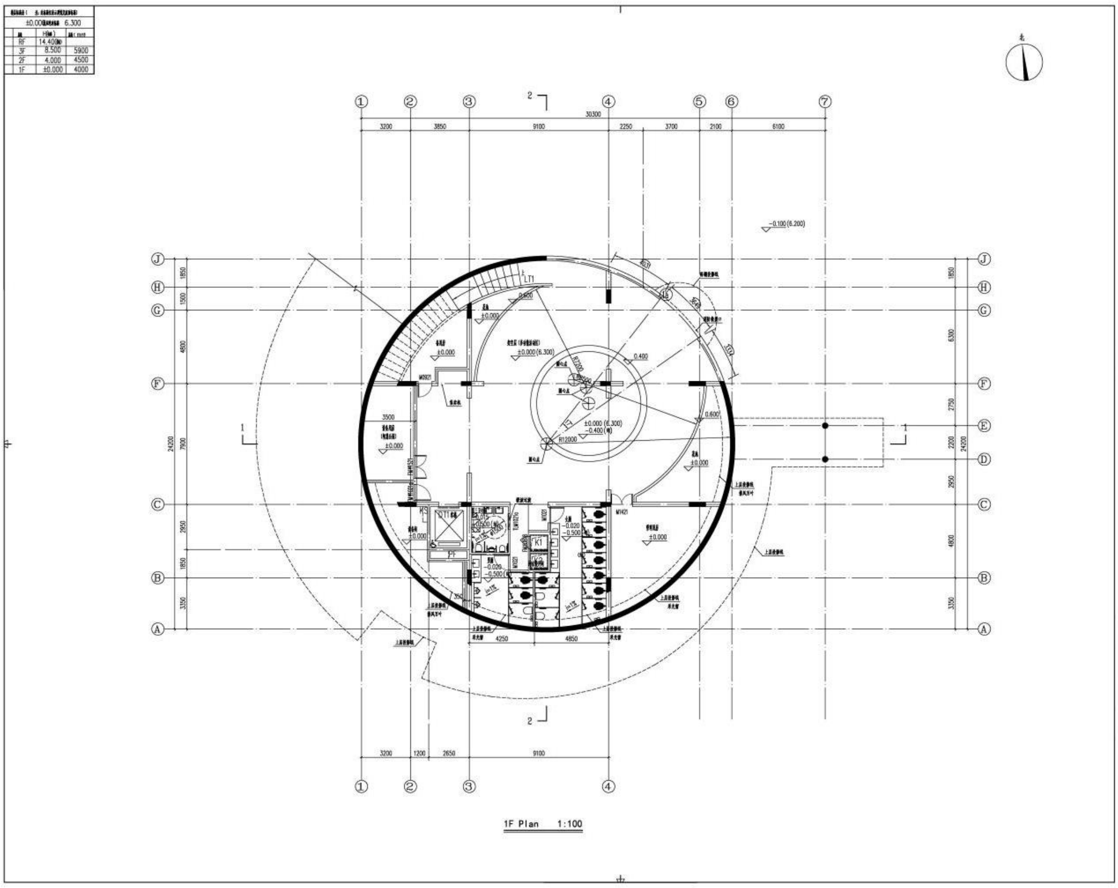

Figure 3.3 – 1F plan

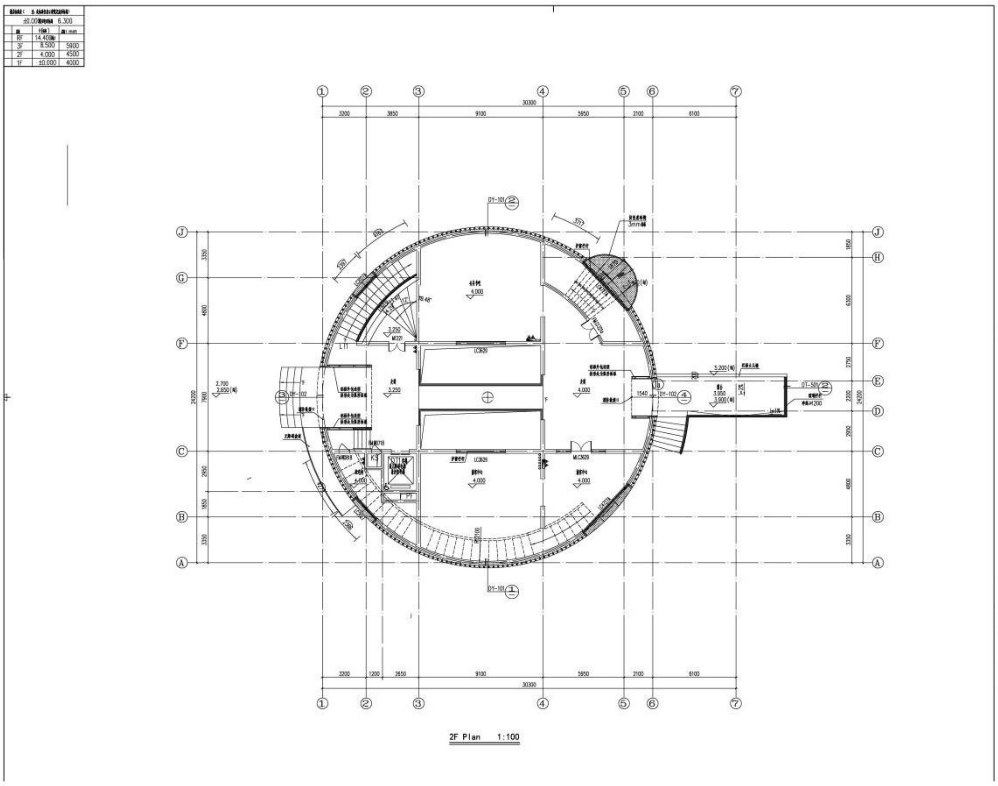

Figure 3.4 – 2F plan

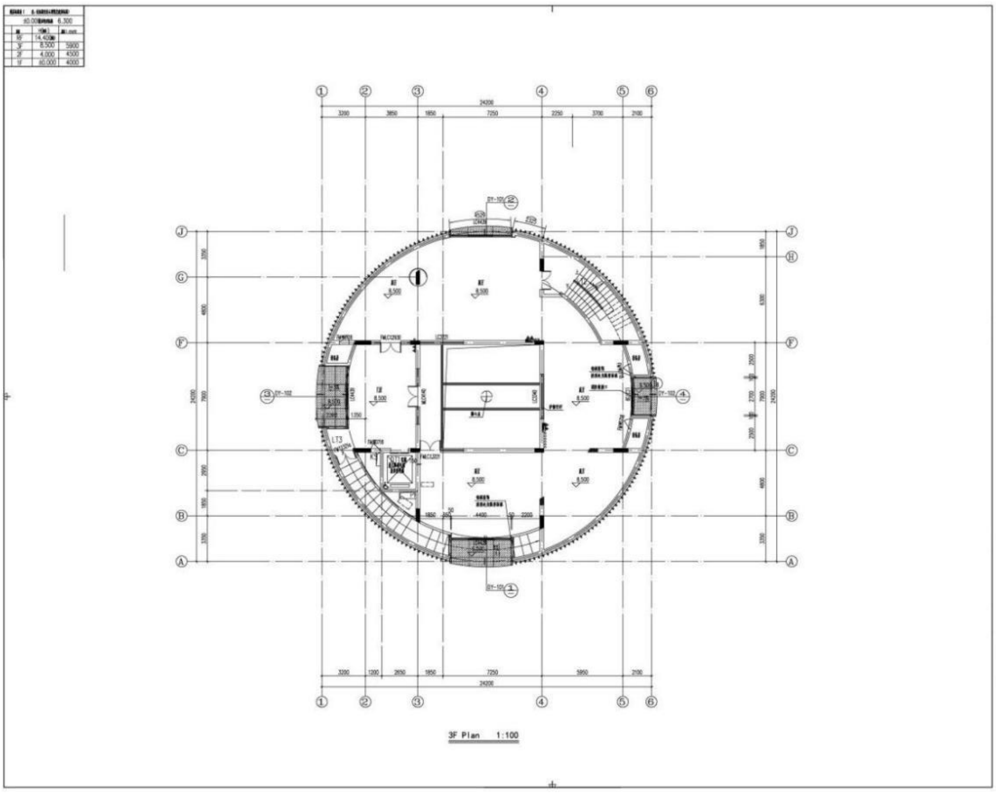

Figure 3.5 – 3F plan

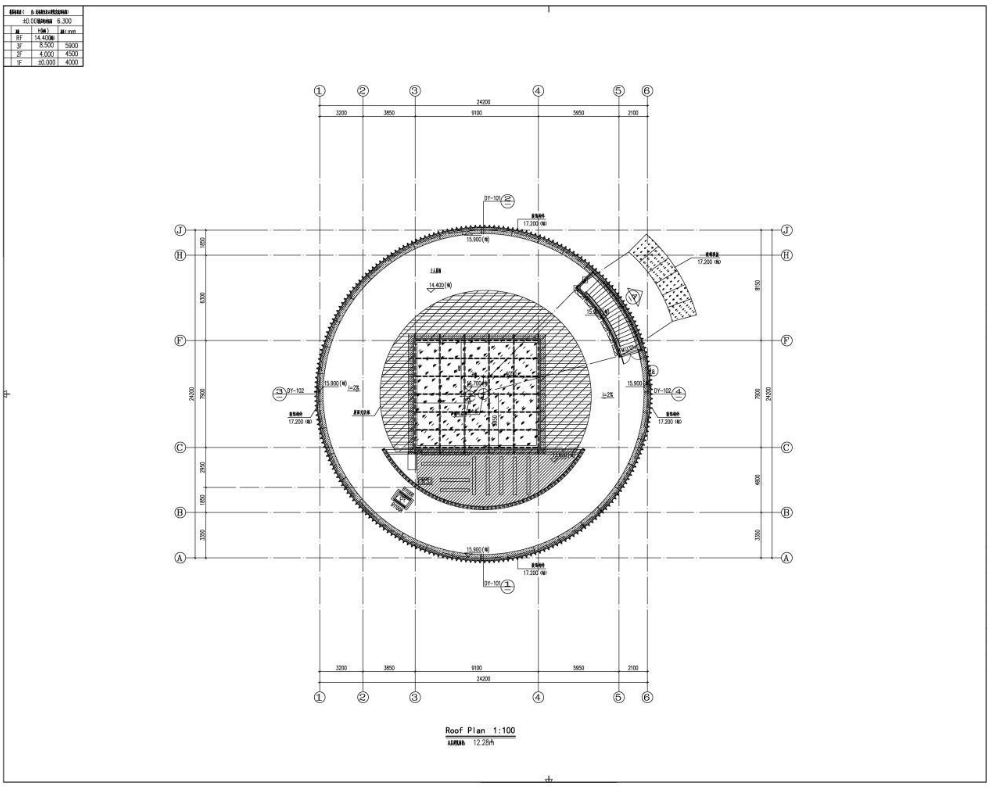

Figure 3.6 – Roof plan

3.2.4 Envelope structure design

The project consists of 3 floors with heights (H) of 4,000mm (1F), 4,500mm (2F), and 5,900mm (3F), while the stairwell on the roof level has a height of 2,800mm. The facade design of the building envelope carefully balances aesthetics and functionality. Through appropriate material selection and structural detailing, the design ensures compliance with energy efficiency requirements while maintaining excellent durability and performance. The project's elevation is shown in Figure 3.8.

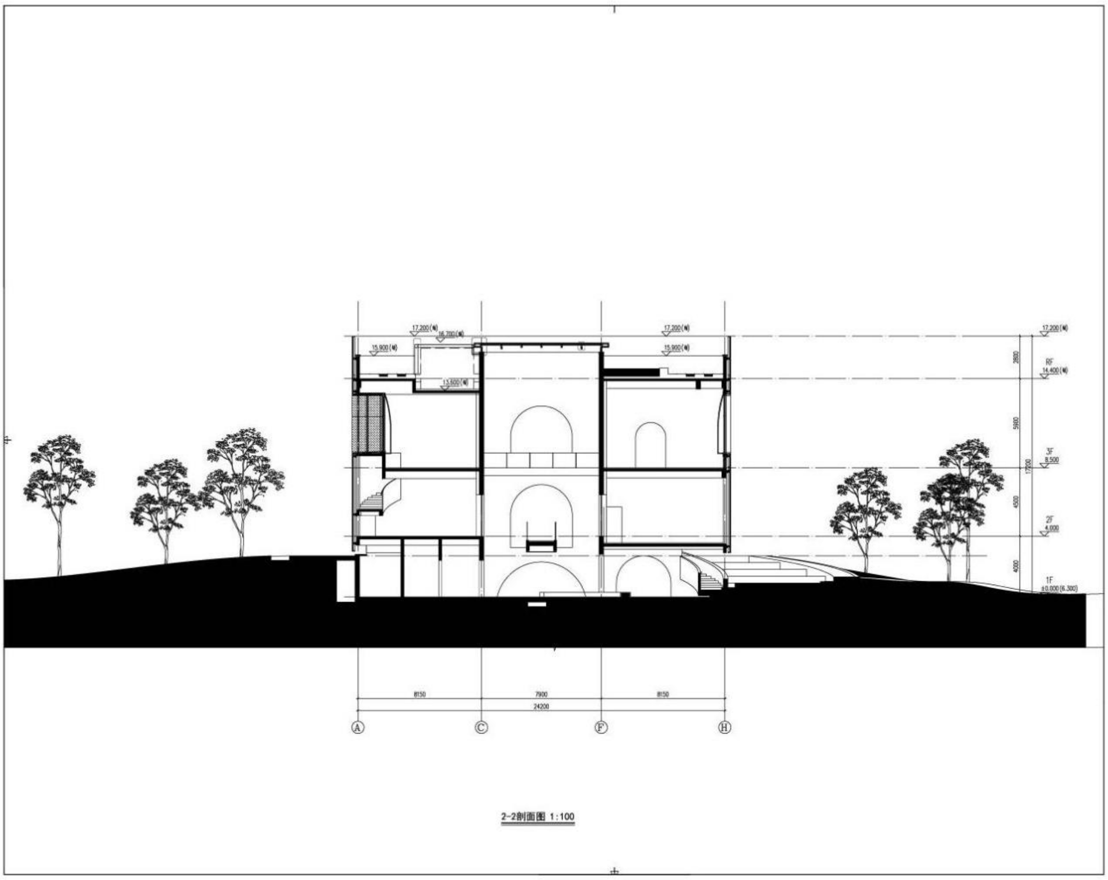

Figure 3.8 – Elevation of XA project

The material selection for the building envelope design comprehensively considered multiple factors including material performance, cost, carbon emissions, and procurement accessibility. The selected materials demonstrate excellent thermal insulation, heat preservation, waterproofing, and fire resistance properties, meeting both energy efficiency requirements and functional demands of the building. Furthermore, they possess high strength and durability to ensure structural stability and long-term service life.

These materials are widely utilized in southern China, facilitating easy procurement while reducing transportation costs and associated carbon emissions during delivery, aligning with sustainable building design principles. Through rational selection and optimization of envelope materials, the project achieves an optimal balance between energy efficiency, comfort, and cost-effectiveness, establishing a solid foundation for sustainable building development. A detailed analysis of the building envelope materials is presented below:

1) Exterior wall structural materials

Cement mortar: Used as the inner layer of exterior walls, cement mortar provides excellent adhesion and abrasion resistance, forming a stable base for subsequent insulation and decorative layers. With mature production technology, low cost, and easy procurement and construction, it is widely adopted.

Aerated concrete: This lightweight, high-strength material offers superior thermal insulation due to its microporous structure, which effectively blocks heat transfer. Widely used in southern China, aerated concrete reduces transportation costs and associated carbon emissions while meeting structural requirements with moderate strength, impermeability, and durability.

Vitrified microsphere insulation mortar: A novel insulation material with low thermal conductivity and fire resistance, composed of vitrified microspheres that enhance wall insulation. Its workability ensures quality during application. Increasingly adopted in southern China, its production is environmentally friendly.

Plastering mortar: As the exterior layer, it protects insulation and provides a smooth surface for decoration. With excellent adhesion and waterproofing, it prevents rain penetration and chemical erosion, extending wall lifespan. Its mature technology and low cost facilitate procurement and construction.

2) Windows, Doors & Skylights

The project employs 6Low-E+12A+6 tempered laminated glass. The Low-E coating reflects solar radiation, reducing summer heat gain and winter heat loss, thereby lowering HVAC energy consumption. Tempered lamination ensures high strength and safety, while high visible light transmittance optimizes natural lighting, minimizing artificial lighting needs. Mature production technology and regional availability align with energy efficiency and daylighting requirements.

3) Roof structural materials (Top to Bottom):

Cement mortar: Protects waterproofing layers and provides a flat surface. Offers adhesion and weather resistance, with mature, low-cost production.

C25 fine-aggregate concrete: High strength and impermeability safeguard the roof structure. Its moderate strength and durability, coupled with regional availability, ensure cost-effective construction.

Waterproof mortar: Specialized for waterproofing, it prevents moisture infiltration. Widely used in southern China with proven technology.

C20 fine-aggregate concrete: Balances strength and impermeability for basic roof protection. Its durability and local accessibility streamline procurement.

XPS board (apparent densityρ=25-32 kg/m^3): High-performance insulation with low thermal conductivity and compressive strength. It minimizes heat transfer, reducing cooling/heating loads. Regionally available with moderate cost.

Reinforced concrete: Provides structural stability and load-bearing capacity. Its strength, plasticity, and durability ensure long-term safety. Mature technology and local usage optimize cost and logistics.

3.2.5 Envelope parameter design

To further optimize the thermal performance, carbon emissions, and cost of the XA project's building envelope, detailed calculations of the envelope parameters were conducted based on the project design. These calculations provide a scientific basis for subsequent multi-objective optimization. Below are the specific design parameters.

1） Facade height

To accurately calculate the surface area and volume of the building envelope—essential for thermal performance, carbon emissions, and cost analysis—the project is divided into three main floors, with an additional roof-level staircase. The specific parameters are listed in Table 3.2.

Table 3.2 – Facade heights of each floor

No.	Floor	Height (H) mm
1	1F	4000
2	2F	4500
3	3F	5900
4	Roof staircase	2800

(Data source: Design drawings)

These parameters serve as the foundation for thermal calculations, carbon emission assessments, and cost estimations. A lower surface-area-to-volume ratio helps minimize heat loss and solar heat gain, thereby improving the building's thermal performance. By utilizing these precise geometric parameters, energy consumption and environmental impact can be more accurately evaluated, supporting data-driven optimization in subsequent design phases.

2）Window area and thermal performance parameters

Windows, as critical elements for daylighting and thermal exchange in buildings, significantly influence thermal performance and lighting efficiency through their area, thermal transmittance (U-value), and solar heat gain coefficient (SHGC). Although fenestration systems generally provide inferior insulation compared to solid walls, properly designed glazing can substantially enhance natural daylighting, thereby improving indoor comfort and reducing artificial lighting energy consumption.

China's current national standard "Assessment Standard for Green Building" (GB/T 50378-2019) mandates specific requirements for natural daylighting in public buildings, stipulating that at least 60% of primary functional spaces must maintain illuminance levels meeting daylighting criteria for an average of ≥4 hours/day. Consequently, this project’s window design must balance thermal insulation performance with adequate natural daylighting provision. Key design parameters are detailed in Table 3.3 below.

Table 3.3 – Window Area Statistics, Average U-value and Solar Heat Gain Coefficient Calculation

<table>
<tr><th>Orientation</th><th>Window ID</th><th>Floor</th><th>Single Window Area（m²）</th><th>Quantity</th><th>Total Window Area（m²）</th><th>U-value (W/m²·K)</th><th>Orientation Average U-value</th><th>Window Shading Coefficient</th><th>External Shading ID</th><th>External Shading Coefficient</th><th>Window Composite SHGC</th><th>Orientation Composite SHGC</th><th>Weighted Average SHGC</th></tr>
<tr><td rowspan="3">East</td><td>LC4727A</td><td>2F</td><td>2.65</td><td>1</td><td>2.65</td><td>2.600</td><td rowspan="3">2.600</td><td>0.400</td><td>SHGC-0</td><td>0.800</td><td>0.278</td><td rowspan="3">0.278</td><td rowspan="10">0.300</td></tr>
<tr><td>LC4727A</td><td>2F</td><td>8.94</td><td>1</td><td>8.94</td><td>2.600</td><td>0.400</td><td>SHGC-0</td><td>0.800</td><td>0.278</td></tr>
<tr><td>LC4727A</td><td>2F</td><td>1.84</td><td>1</td><td>1.84</td><td>2.600</td><td>0.400</td><td>SHGC-0</td><td>0.800</td><td>0.278</td></tr>
<tr><td>South</td><td>LC4727A</td><td>2F</td><td>2.08</td><td>1</td><td>2.08</td><td>2.600</td><td>2.600</td><td>0.400</td><td>SHGC-0</td><td>0.800</td><td>0.278</td><td>0.278</td></tr>
<tr><td>West</td><td>LC2027</td><td>2F</td><td>5.39</td><td>1</td><td>5.39</td><td>2.600</td><td>2.600</td><td>0.400</td><td>SHGC-0</td><td>0.800</td><td>0.278</td><td>0.278</td></tr>
<tr><td rowspan="5">North</td><td>LC4727A</td><td>2F</td><td>9.70</td><td>1</td><td>9.70</td><td>2.600</td><td rowspan="5">2.600</td><td>0.400</td><td>SHGC-0</td><td>0.800</td><td>0.278</td><td rowspan="5">0.314</td></tr>
<tr><td>LC4727A</td><td>2F</td><td>0.50</td><td>1</td><td>0.50</td><td>2.600</td><td>0.400</td><td>SHGC-0</td><td>0.800</td><td>0.278</td></tr>
<tr><td>LC2027</td><td>2F</td><td>5.39</td><td>1</td><td>5.39</td><td>2.600</td><td>0.400</td><td>SHGC-0</td><td>0.800</td><td>0.278</td></tr>
<tr><td>LC4438</td><td>3F</td><td>4.66</td><td>1</td><td>4.66</td><td>2.600</td><td>0.400</td><td>—</td><td>1.000</td><td>0.348</td></tr>
<tr><td>LC4438</td><td>3F</td><td>12.05</td><td>1</td><td>12.05</td><td>2.600</td><td>0.400</td><td>—</td><td>1.000</td><td>0.348</td></tr>
</table>

（Data source: National standards and design drawings）

These parameters provide fundamental data for optimizing the thermal performance of exterior windows, enabling evaluation of thermal exchange across seasons and offering scientific basis for energy-efficient design.

3) Skylight thermal performance parameters

Chinese national and Shenzhen local standards (e.g., Design Standard for Energy Efficiency of Public Buildings) specify that the transparent area of skylights shall not exceed 20% of total roof area. This requirement balances daylighting needs with thermal performance to ensure adequate natural light while minimizing solar heat gain and reducing energy consumption.

In the XA project, the total roof area is 458 m^2 with skylight area of 66.880 m^2 (14.6% of roof area), fully complying with the 20% threshold. Key parameters are detailed in Table 3.4.

Table 3.4 – Skylight Thermal Performance

Window Frame and Glass Nomenclature	U-value（$W/m^2.k$）	Shading Coefficient SC	Visible Light Transmittance (VLT)	Area m^2	Roof Area Ratio
Thermally broken aluminum + Low-E insulated glass (6Low-E+12A+6)	2.504	0.240	0.620	66.880	0.146

(Data source: National standards and design drawings)

The optimized skylight design meets energy standards while enhancing indoor daylighting and overall building performance.

4) Envelope thermal performance, carbon emission factors & unit costs

To support scientific optimization of the XA project's envelope, this study compiles detailed material-specific thermal parameters, carbon emission factors, and unit costs. These data underpin subsequent thermal optimization, carbon assessment, and cost analysis. Refer to Table 3.5 for specifications.

Table 3.5 – Thermal Performance Parameters, Carbon Emission Factors and Unit Prices of Building Envelope Components

Component	Material Name	Thermal Performance			Carbon Emission Factor kg CO2/m³	Unit Price（RMB/m2）	
		λ (W/m.k)	S(W/m2.k)	R(m2.k/W)			
Exterior Wall	M20 Cement Mortar	0.930	11. 370	0. 022	266	20mm	25.03
						30mm	43.05
	Aerated Concrete	0.220	4. 286	0. 727	336	150mm	550.81
						200mm	632
	Vitrified Microsphere Insulation Mortar	0. 080	1. 754	0. 313	154	20mm	42
						30mm	47
	M20 Plastering Mortar	0. 085	1.190	0. 059	380	20mm	22
						30mm	30
Doors & Windows	Laminated Glass	U-value (W/m2.k)	SC	VLT	574	6Low-E+12A+6	850
		2.600	0.400	0.620			
Skylight	Laminated Glass	U-value (W/m2.k)	SC	VLT	574	6Low-E+12A+6	850
		2.504	0.240	0.620			
Roof	M20 Cement Mortar	0. 930	11. 370	0. 022	266	20mm	20.03
						30mm	33.83
	C25 Fine Aggregate Concrete	1. 510	15. 245	0.033	295	40mm	35
						50mm	40
Component	Material Name	Thermal Performance			Carbon Emission Factor kg CO2/m³	Unit Price（RMB/m2）	
		λ (W/m.k)	S(W/m2.k)	R(m2.k/W)			
Roof	Waterproof Mortar	0. 930	11. 306	0.005	365	5mm	50
						10mm	55
	C20 Fine Aggregate Concrete	1. 740	17. 200	0. 017	288	30 mm	30
						40 mm	40
	XPS Board (p=25-32)	0. 030	0.384	2. 222	46	80mm	128.8
						100mm	136
	C30 Reinforced Concrete	1. 740	17. 200	0.086	295	150mm	350
						100mm	335

（Data source: National standards and project settlement documents）

Conclusions to Chapter 3

Using Shenzhen's XA near-zero-energy public building as a case study, this chapter demonstrates climate-responsive envelope design for subtropical regions. Key features include circular geometry to minimize surface-area-to-volume ratio, and material selection (aerated concrete, vitrified microsphere mortar) optimizing thermal performance and local availability. Detailed parametric design covers wall/roof assemblies, fenestration systems (6Low-E+12A+6 glazing), and skylight configurations compliant with the ≤20% roof area regulation. All designs adhere to national standards (GB 50189, GB/T 50378) for thermal, carbon, and cost parameters, providing baseline data for Chapter 4's optimization.

CHAPTER 4 MULTI-OBJECTIVE DESIGN OPTIMIZATION OF SUSTAINABLE BUILDING ENVELOPES IN SUBURBAN AREAS

4.1 Optimization objectives and model setup

4.1.1 Optimization objectives

In sustainable building design and construction, the performance of the building envelope is a critical factor influencing energy efficiency and environmental impact. This project selects the thermal performance, carbon emissions, and cost of the building envelope as optimization objectives to achieve a comprehensive balance between energy efficiency, environmental sustainability, and economic viability.

1)Thermal performance

Thermal performance is a key indicator of the insulation effectiveness of the building envelope. Given the project's location in southern China, insulation performance is particularly crucial. The quality of thermal performance directly affects building energy consumption, with thermal transmittance (U-value) and thermal inertia index (D-value) serving as the primary metrics. The U-value reflects the heat transfer capacity of the envelope, while the D-value measures its ability to buffer external temperature fluctuations. By optimizing material thickness, the U-value can be reduced, and the D-value enhanced, thereby improving overall thermal insulation performance.

2) Carbon emissions

Carbon emissions are a vital metric for assessing the environmental impact of sustainable buildings. The carbon footprint of the building envelope primarily stems from material production, transportation, and construction processes. Due to variations in construction techniques and transportation distances across projects, even identical materials may yield significantly different total carbon emissions. Furthermore, accurately quantifying emissions during envelope construction remains challenging. This project therefore focuses on optimizing material selection based on embodied carbon (kg CO_2/m^3). By adjusting material thickness and selecting low-carbon material combinations, carbon emissions can be minimized while meeting thermal performance requirements.

3) Cost

Cost is an essential consideration in sustainable envelope construction. Projects must balance thermal performance and carbon reduction with budgetary constraints. This project incorporates cost as an optimization objective, aiming to identify material thicknesses and combinations that satisfy thermal and environmental criteria at minimal expense.

This project integrates thermal performance (*U*-value and *D*-value), embodied carbon, and cost as multi-objective optimization targets. Since thermal performance correlates with intrinsic material properties (e.g., thermal conductivity λ, heat capacity S) and is directly influenced by material thickness, the optimization variables will focus on the thicknesses of envelope components. Scientific optimization methods will be employed to achieve Pareto-optimal solutions across all three objectives.

4.1.2 Selection of independent variables

This structured approach ensures compliance with regulatory requirements while optimizing the building envelope's performance, sustainability, and cost-effectiveness. The material thicknesses in this project were determined based on national and regional standards, energy-efficient design codes, and practical construction requirements. These standards include, but are not limited to:

-Design Standard for Energy Efficiency of Buildings (GB 50189)

-Code for Acceptance of Construction Quality of Building Ground (GB 50209)

-Technical Specification for Application of Autoclaved Aerated Concrete (JGJ/T 17)

-Technical Specification for External Wall Insulation Engineering (JGJ 144)

-Code for Acceptance of Construction Quality of Roofing (GB 50207)

-Code for Design of Concrete Structures (GB 50010)

Material thicknesses were selected by balancing constructability, thermal performance optimisation, and cost-effectiveness to ensure the results meet engineering requirements while achieving comprehensive optimisation of thermal performance, carbon emissions, and cost.

For the building envelope, windows, doors, and skylights all use thermally broken aluminium frames with Low-E insulated glass (6Low-E+12A+6). Since their design area, carbon emissions, and cost are fixed values, these components were excluded from optimization. The focus was instead placed on optimizing the thicknesses of exterior wall and roof materials, as detailed in the following table 4.1.

Table 4.1 – Wall Material Types and Thickness Specifications

Category (Component)	Parameter (Material type)	Variable type	Thickness options (mm)
Exterior wall	Cement mortar	Discrete	20, 30
	Aerated concrete		150, 200
	Vitrified microsphere insulation mortar		25, 30
	M20 Plastering mortar		20, 30
Doors & Windows	Laminated glass	Fixed	6Low-E+12A+6
Skylight	Laminated glass		6Low-E+12A+6
Roof	Cement mortar	Discrete	20, 30
	C25 Fine-aggregate concrete		40, 50
	Waterproof mortar		5, 10
	C20 Fine-aggregate concrete		30, 40
	XPS board(ρ=25-32)		80, 100
	Reinforced concrete		100, 150

4.1.2Model establishment

The sum of the thicknesses of M20 cement mortar, aerated concrete, vitrified microsphere insulation mortar, and M20 plastering mortar from the interior to the exterior determines the exterior wall thickness of this project. The roof thickness, from the outer surface inward, consists of M20 cement mortar, C25 fine aggregate concrete, waterproof mortar, C20 fine aggregate concrete, extruded polystyrene board (density: 25-32 kg/m³), and C30 reinforced concrete.

4.1.3 Constraints

In building envelope design, the thickness of walls and roofs is a key parameter that affects building performance. To ensure the safety, stability, and functionality of the building, the thickness of walls and roofs must meet the requirements specified in relevant national standards and regulations.

1）Constraint 1

-Exterior wall thickness：$d\_wall \leq 0.350$ m；

-Roof thickness: $d_{roof} \le 0.400$ m

The specific calculation formulas 4.1, 4.2 are shown in Section.

$$d_{wall} = d_{M20\ cement\ mortar} + d_{aerated\ concrete} + d_{vitrified\ microsphere\ insulation\ mortar} + d_{M20 plastering mortar} \quad (4.1)$$

$$d_{roof} = d_{M20\ cement\ mortar} + d_{C25\ fine\ aggregate\ concrete} + d_{waterproof\ mortar} + d_{C20\ fine\ aggregate\ concrete} + d_{C30\ reinforced\ concrete} \quad (4.2)$$

After satisfying Constraint 1, the determination of Constraint 2 is carried out. If Constraint 1 is not satisfied, the values should be reselected.

2）Constraint 2

According to the requirements for thermal design of building envelopes in hot-summer and warm-winter regions specified in the Chinese National Standard "Design Standard for Energy Efficiency of Public Buildings" GB 50189-2015, the design constraints for the thermal transmittance (K-value) and thermal inertia index (Dm) of the envelope are as follows:

Thermal performance limits for exterior walls (K_wall, Dm_wall), the specific calculation formula 4.3 is shown in Section.

$$\text{If } K\_wall \le 0.8, \text{then } Dm\_wall \le 2.5;$$

$$\text{If } K\_wall \le 1.5, \text{then } Dm\_wall > 2.5 \quad (4.3)$$

Thermal performance limits for roofs (K_roof, Dm_roof), the specific calculation formula 4.4 is shown in Section.

$$\text{If } K\_roof \le 0.5, \text{then } Dm\_roof \le 2.5;$$

$$\text{If } K\_roof \le 0.8, \text{then } Dm\_roof > 2.5 \quad (4.4)$$

Among them, the calculation methods for the thermal transmittance (K-value) and thermal inertia index (Dm) of the building envelope are as follows:

To calculate the thermal transmittance (K-value) and thermal inertia index (Dm), the thermal resistance of the building envelope is first calculated. Thermal resistance is the ratio of the material thickness to its thermal conductivity, and the formula 4.5 is as follows.

$$R=d/\lambda, \tag{4.5}$$

Where: d is the material thickness

Λ is the thermal conductivity of the material

Next, the total thermal resistance of the building envelope is calculated as follows formula 4.6,4.7.

Rwall=Ri+(RM20cement mortar+Raerated concrete+
Rvitrified microsphere insulation mortar+RM20 plastering mortar)+Re (4.6)

Rroof=Ri+(RM20cement mortar+RC25fine aggregate concrete+
Rwaterproof mortar+RC20fine aggregate concrete+RXPS(ρ=25−32)+
RC30reinforcedconcrete)+Re (4.7)

Where: Ri- Internal surface thermal resistance (0.11 $m^2 \cdot K/W$);

Re-External surface thermal resistance (0.04 $m^2 \cdot K/W$)。

Once the total thermal resistance of the building envelope is obtained, the thermal transmittance (K-value) can be calculated. The K-value is the reciprocal of the total thermal resistance, expressed as formula 4.8.

$$K=1/R \tag{4.8}$$

The thermal inertia index Dm of the building envelope is calculated using the following formula 4.9.

$$Dml=\sum(Si\times Ri) \tag{4.9}$$

Where: Si: Thermal storage coefficient of the ii-th material ($W/m^2\cdot K$)

Ri: Thermal resistance of the ii-th material ($m^2\cdot K/W$).

4.1.4 Output results

After performing multi-objective optimization, when the calculation results simultaneously satisfy Constraint 1 (i.e., the exterior wall thickness does not exceed 0.350 m and the roof thickness does not exceed 0.400 m) and Constraint 2 (i.e., the thermal transmittance and thermal inertia index of the walls and roof meet relevant standard requirements), the following outputs will be generated to guide the project's design and construction, and to demonstrate the optimized performance indicators of the building envelope.

Material thickness indicators

The optimized output includes the specific thicknesses of each material layer for both the exterior walls and the roof:

For the walls, this includes the thickness of M20 cement mortar, aerated concrete, glass bead thermal insulation mortar, and M20 plastering mortar.

For the roof, it includes the thickness of M20 cement mortar, C25 fine aggregate concrete, waterproof mortar, C20 fine aggregate concrete, extruded polystyrene board (XPS, ρ=25–32 kg/m^3), and C30 reinforced concrete.

Thermal performance indicator

These include the thermal transmittance (K-value) and thermal inertia index (D-value):

For the walls: K_wall and D_wall

For the roof: K_roof and D_roof

These indicators serve as quantitative benchmarks for evaluating the thermal performance of the building envelope, ensuring that the thermal performance meets national energy efficiency design standards during the design process.

Cost estimation results

In terms of cost, the outputs include the construction costs for both the walls and the roof, denoted as Cost_wall and Cos_troof respectively. The cost estimation is based on the project's design parameters and the optimized results using the following formula 4.10.

$$\text{Cost}=\sum(\text{Envelope Area}\times\text{Unit Price of Each Material}) \quad (4.10)$$

Carbon emission calculation

Regarding carbon emissions, the carbon footprint of both the exterior walls and the roof will be calculated separately, denoted as CO2_wall and CO2_roof. The carbon emission calculation formula is as follows formula 4.11.

$$\text{CO2}=\sum(\text{Envelope Area}\times\text{Carbon Emission Factor of Each Material}) \quad (4.11)$$

4.2 Multi-objective optimization software

4.2.1 Multi-objective optimization methods and algorithms

Multi-objective optimization is a crucial branch of operations research and decision science, aiming to simultaneously optimize multiple conflicting objective functions. Common multi-objective optimization methods include[31].

1）Traditional mathematical programming methods

Weighted Sum Method: Transforms multiple objectives into a single-objective problem by assigning weight coefficients to each objective function. These weights reflect the decision-maker's relative preference for different objectives. For example, in a bi-objective optimization of cost and environmental impact, greater weight can be assigned to environmental impact if prioritized. While simple to implement, weight selection is subjective, and it may fail to capture all Pareto optimal solutions.

Goal Programming: Allows setting target values (goals) for each objective function and minimizes deviations from these targets. For instance, in production planning, targets can be set for maximizing output and minimizing costs, with optimization reducing deviations. This method effectively handles priority relationships among objectives but may face computational complexity with numerous goals.

2）Modern intelligent algorithms

Genetic Algorithm (GA): Simulates biological evolution through selection, crossover, and mutation operations. Its strengths include parallel processing and the ability to explore multiple solutions simultaneously, making it suitable for complex, nonlinear, and multimodal problems (e.g., engineering design optimization). However, it may suffer from premature convergence (local optima) and computational inefficiency[32].

Particle Swarm Optimization (PSO): Inspired by bird flocking behavior, particles adjust their trajectories in the solution space based on individual and collective experience. Advantages include simplicity and few tuning parameters. In multi-objective optimization, enhanced fitness evaluation mechanisms can handle multiple objectives (e.g., rapid convergence in function optimization). However, it struggles with complex constraints[33].

Non-dominated Sorting Genetic Algorithm II (NSGA-II): Enhances GA with non-dominated sorting and crowding distance operators to maintain population diversity and converge efficiently to the Pareto front. Widely applied in engineering and economic planning, it provides balanced solution sets. Performance depends heavily on parameters (e.g., population size, crossover probability).

4.2.2 Commonly used multi-objective optimization software

1）MATLAB

Provides a powerful optimization toolbox covering various traditional and intelligent optimization algorithms, suitable for solving complex multi-objective optimization problems. It offers excellent data visualization capabilities for result analysis and is widely used in academia and industry.

2）Python and related libraries

Python boasts rich multi-objective optimization libraries such as DEAP and PyGMO. Its open-source nature and strong community support allow flexible customization of the optimization process and integration with data processing and machine learning libraries. However, compared to Matlab, it is slightly inferior in graphical interfaces and certain specialized optimization functions.[34]

3）Excel solver

Suitable for simple multi-objective optimization problems, integrated into

Excel spreadsheets for easy operation and intuitive data presentation. Its capability to solve complex problems is limited, making it more suitable for small-scale or relatively simple scenarios.[35]

4.2.3 Selection of MATLAB

In this project, MATLAB is chosen as the primary computational tool for the multi-objective optimisation design of sustainable building envelopes in suburban areas. MATLAB, developed by MathWorks, is a high-performance numerical computing and visualization software with powerful mathematical functions and extensive toolboxes, widely applied in engineering, research, and academia. The advantages of MATLAB in this project include:

1）Multi-objective optimization algorithms

Matlab's Global Optimization Toolbox provides various algorithms for multi-objective optimization. For example:

Genetic Algorithm (GA): Simulates natural selection and genetic mechanisms to find global optima in complex search spaces.

Non-dominated Sorting Genetic Algorithm II (NSGA-II): Specifically designed for multi-objective optimization, generating Pareto fronts to help decision-makers weigh trade-offs between objectives.

2）Problem definition and solving

In Matlab, users can easily define optimization problems, including objective functions, decision variables, and constraints. By calling functions like gamultiobj (a genetic algorithm-based multi-objective optimization function), multi-objective problems can be directly solved. For this project, the optimization process includes:

Defining objective functions: Heat transfer coefficient (K), carbon emissions (CO_2), and cost.

Setting decision variables: Wall thickness, window area, etc [37].

Adding constraints: Such as limits on wall thickness, heat transfer coefficient, and window-to-wall ratio.

Selecting optimization algorithms: e.g., NSGA-II.

Running optimization and obtaining Pareto fronts.

3） Result analysis and visualization

Matlab offers rich plotting functions to visualize optimization results. For example:

Pareto front plots: Illustrate trade-offs between objectives.

Convergence curves: Evaluate algorithm performance.

These tools aid researchers in interpreting results and supporting decision-making.

4）Integration with other tools

MATLAB supports integration with other software (e.g., EnergyPlus for building performance simulation) to validate optimization results. Importing and analyzing simulation data enhances accuracy and reliability.

In summary, MATLAB's computational power, comprehensive toolboxes, and flexible programming environment make it ideal for this project's multi-objective optimisation. It enables the efficient solving of complex problems and provides a scientific basis for sustainable building envelope design in suburban areas.

4.3 MATLAB model construction and code implementation

4.3.1 MATLAB model parameters and solution process

The multi-objective optimization in this project uses MATLAB as the primary tool, with the following workflow:

1)Parameter Definition

Specify materials and their thicknesses for walls and roofs (selected from Table 4.1).

Define window parameters, including wall and roof areas.

2)Model Construction

Define design variables (e.g., wall and roof thicknesses).

Set objective functions: Heat transfer coefficient (K), thermal inertia index (Dm), carbon emissions, and cost.

3) Optimization phase

Select NSGA-II as the optimization method.

Configure parameters: Population size = 200, maximum iterations = 100, convergence tolerance = 1e-6.

Run the optimization program.

4)Result analysis

Extract optimized results (thicknesses, K values, carbon emissions, costs).

Generate comparative plots to visualize trade-offs between objectives for decision-making. The detailed workflow is illustrated in Figure 4.1.

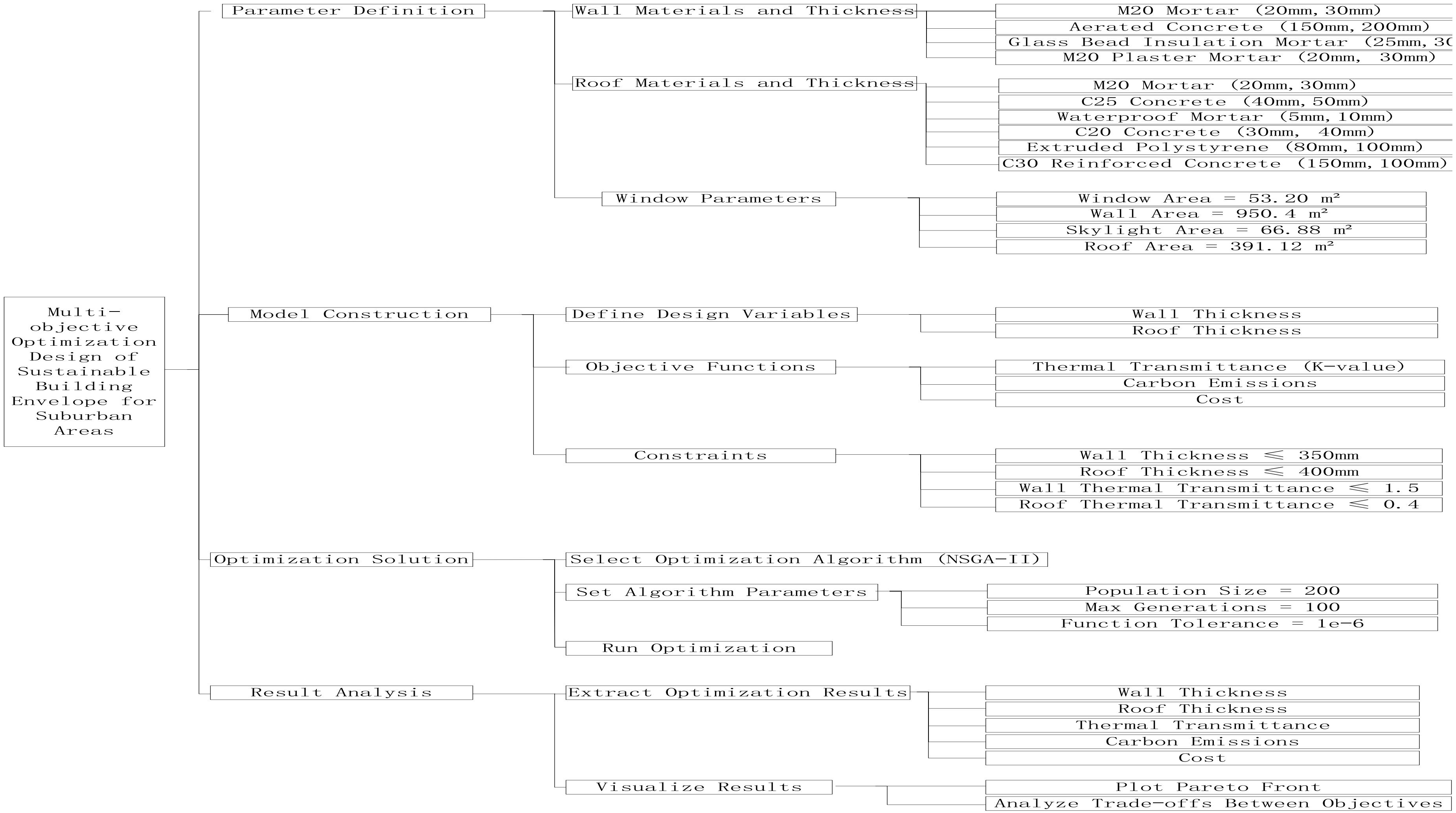

Figure 4.1 – MATLAB model and solution flowchart

4.3.2 Matlab code implementation

The MATLAB code is primarily developed around the project's optimization objectives and consists of four main components: parameter definition, algorithm determination, result output, and graphical visualization, as detailed below:

First, parameter definition.

At the beginning of the code, detailed definitions are made for the relevant parameters of the walls and roofs. Wall parameters include wall area, layers of materials, thickness ranges, thermal conductivity, heat capacity, carbon emission factors, and cost. Similarly, roof parameters include roof area, material layers, thickness ranges, thermal conductivity, heat capacity, carbon emission factors, and cost. In addition, baseline unit prices and design thicknesses are also defined. These parameters provide foundational data support for subsequent optimization calculations and comparative analysis.

Second, determining the optimization algorithm.

In the code, an exhaustive search method is employed to explore feasible optimization solutions. For wall optimization, all possible combinations of layer thicknesses are generated using the ndgrid function, stored as combinations_wall. Each combination is then checked to ensure that the total thickness does not exceed 0.35 meters. For those combinations that meet the thickness constraint, further calculations are performed to determine their thermal resistance, K-value (thermal transmittance), D-value (thermal inertia index), carbon emissions, and cost. During this process, internal and external surface resistances (Ri_wall and Re_wall) are considered to ensure the accuracy of the results. Valid solutions that satisfy all constraints are stored in the valid_solutions_wall array. The optimization process for the roof follows a similar approach, with the only difference being that the total thickness must not exceed 0.40 meters. All possible combinations (combinations_roof) are generated, filtered, and calculated accordingly to obtain valid solutions stored in valid_solutions_roof.

Third, result output.

After completing the optimization calculations, the code checks whether any feasible solutions were found. If so, the valid solutions are sorted by cost in ascending order, and the solution with the lowest cost is selected as the optimal one. Detailed information on the optimal solution for both the wall and roof is then output, including the thickness of each material layer, K-value, D-value, carbon emissions, and cost.

Fourth, graphical visualization.

The PlotOptimizationResults function is called to generate multiple charts comparing the original design and the optimized design. The comparison plots include:

-Thickness comparison of each material layer in the wall

-Thickness comparison of each material layer in the roof

-Comparison of K-values and D-values between the wall and roof

-Comparison of CO_2 emissions between the wall and roof

-Cost comparison between the wall and roof

When writing the plotting code, appropriate settings for layout, labels, legends, and grid lines are applied to enhance the readability and visual appeal of the charts. Additionally, detailed performance indicators of both the original and optimized designs are printed in the command window, allowing readers to intuitively understand the effectiveness of the optimization.

The complete code can be found in Appendix A Wall Roof Optimization.

4.4 MATLAB output results

To write code in MATLAB that obtains the optimized results and compares them with the original design values, and then summarizes these findings as shown in Table 4.4-1 Comparison of Design Values and Optimized Values for the Envelope Structure, follow this procedure. Additionally, graphical comparisons are provided, including:

-A comparison chart of the thicknesses of each material layer in the wall (Figure 4.4-1)

-A comparison chart of the thicknesses of each material layer in the roof (Figure 4.4-2)

-A comparison chart of K-values and D-values for walls and roofs (Figure 4.4-3)

-A comparison chart of CO_2 emissions for walls and roofs (Figure 4.4)

-A comparison chart of costs for walls and roofs (Figure 4.5)

4.4.1 Optimal exterior wall and roof solutions

The Matlab running results include the optimized values for the walls and roof, as well as various indicators for both the design and optimization. The specific content is as follows:

Wall Optimal Solution

-M20 Cement Mortar Thickness: 0.025 m

-Aerated Concrete Block Thickness: 0.200 m

-Perlite Insulation Mortar Thickness: 0.020 m

-M20 Plastering Mortar Thickness: 0.030 m

-K=0.592 W/m²K, D=5.061, CO_2=83913.5 kg, Cost=695400.0 RMB

Roof Optimal Solution

-M20 Cement Mortar Thickness: 0.020 m

-C25 Fine Aggregate Concrete Thickness: 0.040 m

-Waterproof Mortar Thickness: 0.005 m

-C20 Fine Aggregate Concrete Thickness: 0.030 m

-Extruded Polystyrene Board Thickness: 0.080 m

-Reinforced Concrete Thickness: 0.150 m

-K=0.336 W/m²K, D=3.512, CO_2=29526.4 kg, Cost=1641730.8 RMB

Design Scheme Indicators

-Wall: K=0.476, D=6.324, CO_2=103141.5 kg, Cost=719150.0 RMB

-Roof: K=0.272, D=4.364, CO_2=36806.8 kg, Cost=1722746.0 RMB

Optimized Scheme Indicators

-Wall: K=0.592, D=5.061, CO_2=83913.5 kg, Cost=695400.0 RMB

-Roof: K=0.336, D=3.512, CO_2=29526.4 kg, Cost=1641730.8 RMB

4.4.2 Comparison charts

The summary of the optimization and calculation results is shown in the following Table 4.2.

Table 4.2 – Comparison of design values and optimized values for the envelope structure

Component	Material	Design					Optimized				
		Thickness（mm）	K W/(m²·K)	D	CO2（Kg）	Cost（RMB）	Thickness（mm）	K W/(m²·K)	D	CO2（Kg）	Cost（RMB）
Wall	M20 Cement Mortar	25	0.476	6.324	103141.5	719150.0	25	0.592	5.061	83913.5	695400.0
	Aerated Concrete Block	250					200				
	Perlite Insulation Mortar	30					20				
	M20 Plastering Mortar	35					30				
Roof	M20 Cement Mortar	20	0.272	4.364	36806.8	1722746.0	20	0.336	3.512	29526.4	1641730.8
	C25 Fine Aggregate Concrete	50					40				
	Waterproof Mortar	5					5				
	C20 Fine Aggregate Concrete	30					30				
	Extruded Polystyrene Board	100					80				
	Reinforced Concrete	200					150				

4.4.3 Comparison between optimized and design values

The comparison charts of various performance indicators are shown in Figures 4.2 to 4.6.

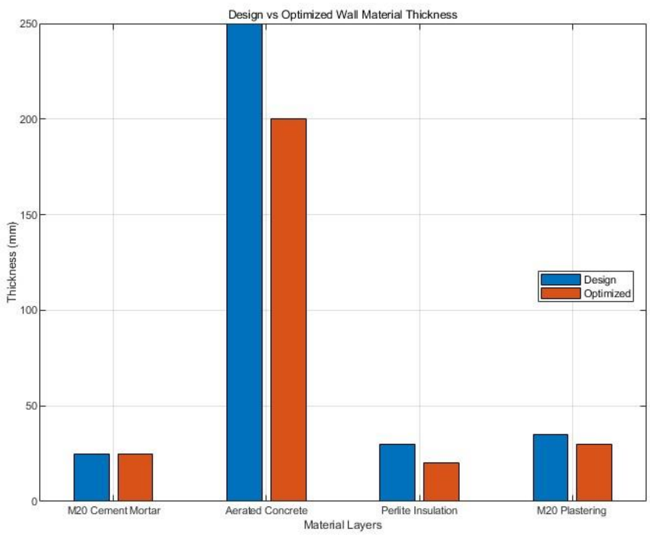

Figure 4.2 – Comparison chart of the thicknesses of each material layer in

the wall

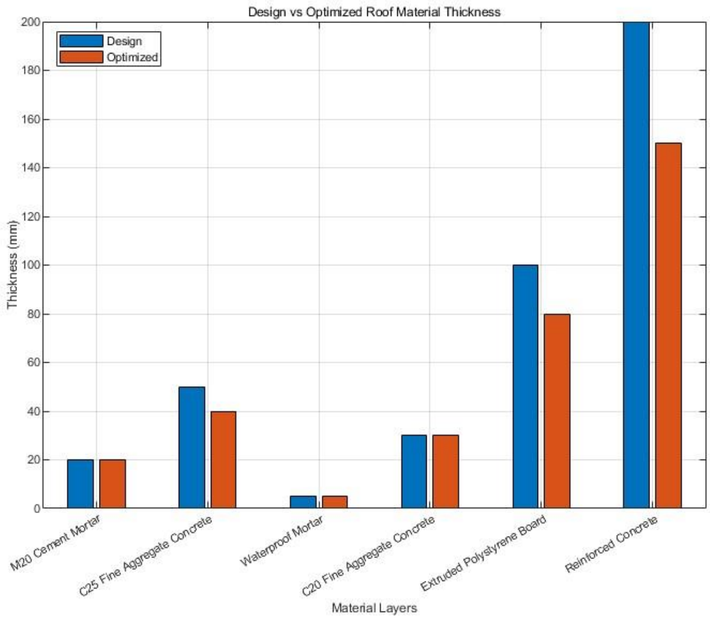

Figure 4.3 – Comparison chart of the thicknesses of each material layer in the roof

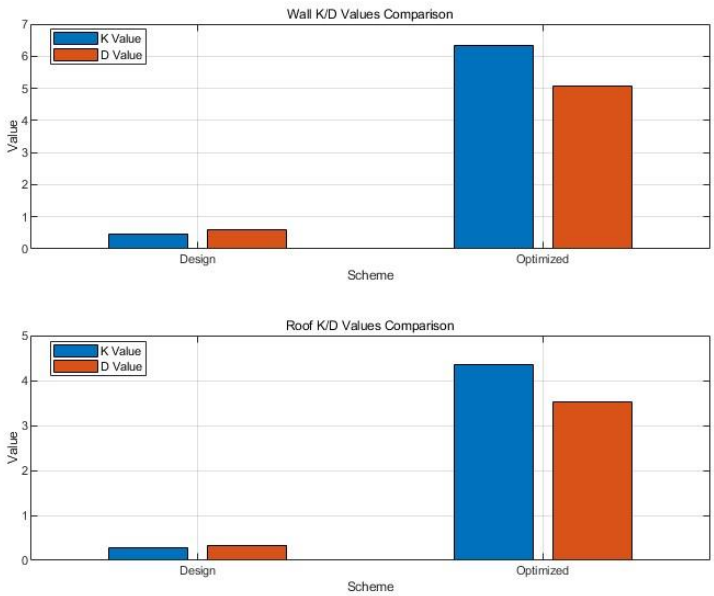

Figure 4.4 – Comparison chart of K-values and D-values for walls and roofs

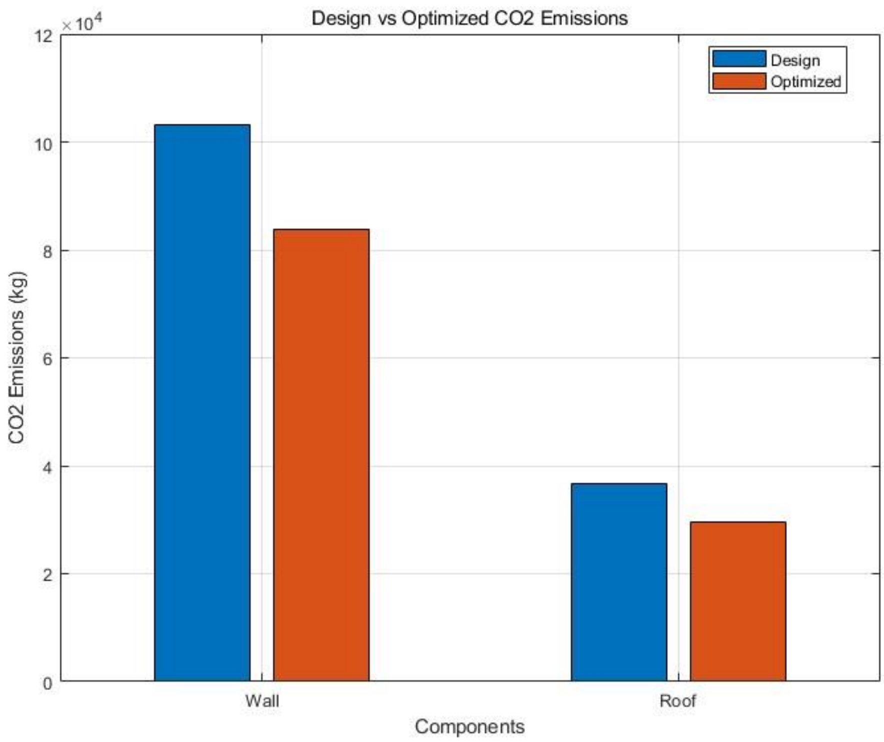

Figure 4.5 – Comparison chart of CO_2 emissions for walls and roofs

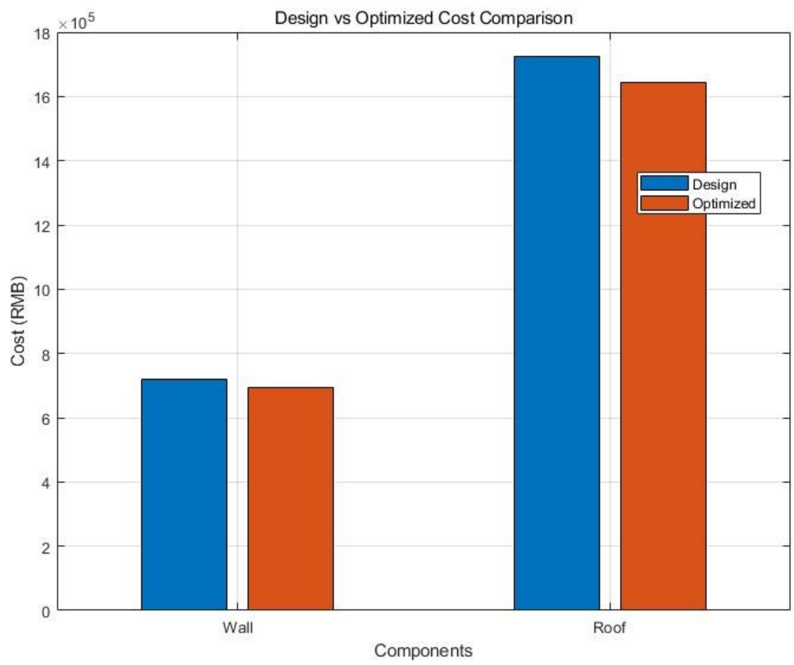

Figure 4.6 – Comparison chart of costs for walls and roofs

Conclusions to Chapter 4

This chapter presents the multi-objective optimization process for the sustainable building envelope design of the XA project, using MATLAB with the NSGA-II algorithm. The optimization focuses on three key objectives: thermal performance (K-value and D-value), carbon emissions, and cost, with material thicknesses as the primary variables. Constraints include maximum allowable thicknesses for walls (0.35 m) and roofs (0.40 m), as well as thermal performance requirements based on China's *Design Standard for Energy Efficiency of Public Buildings* (GB 50189-2015). The optimization results demonstrate significant improvements: the exterior wall's K-value decreases to 0.592 W/(m^2·K) with a 19,228 kg reduction in CO_2 emissions (18.6%) and a 3.3% cost savings, while the roof achieves a K-value of 0.336 W/(m^2·K) with a 7,280.4 kg reduction in CO_2 emissions (19.8%) and a 4.7% cost reduction. The optimised solutions fully comply with Shenzhen's energy efficiency standards (SJG 44-2025), confirming the effectiveness of the multi-objective approach in balancing thermal performance, environmental impact, and economic feasibility. The chapter also details the MATLAB model setup, constraint implementation, and result analysis, providing a comprehensive framework for similar optimization studies in sustainable building design.

CHAPTER 5 RESEARCH CONCLUSIONS AND PROSPECTS

5.1 Conclusions

Suburban areas, as an important component of urban development, play a crucial role in promoting the green transformation of the entire city through sustainable construction. This study focuses on the building envelope of sustainable suburban buildings, using the XA project in Shenzhen's suburbs as a case study to conduct relevant research. The aim is to achieve comprehensive improvements in thermal performance, carbon emissions, and cost of building envelopes, providing technical guidance and practical references for the sustainable development of suburban buildings. The research concludes as follows:

Based on the demands of urban development, sustainable architecture, and control of building carbon emissions, this study proposes optimizing urban suburban sustainable buildings as a design objective and conducts multi-objective optimization design through building models. The model uses the thicknesses of various materials composing the envelope as variables, with total envelope thickness and standardized energy-saving design criteria for public buildings' thermal performance serving as constraints, ultimately achieving optimal thermal performance, carbon emission levels, and cost objectives for the project.

In terms of research methodology, this study employed the advanced multi-objective optimization algorithm NSGA-II. This algorithm features strong global search capabilities and an efficient non-dominated solution generation mechanism, effectively addressing complex multi-objective optimization problems. It not only rapidly converges towards the Pareto front, offering a series of balanced solutions but also fully considers the relationships among multiple objectives, avoiding entrapment in local optima. By constructing a reasonable optimization model and leveraging the advantages of the NSGA-II algorithm, this study provides scientific basis and technical support for the design of sustainable building envelopes in suburban areas.

Regarding optimization outcomes, there was a notable improvement over unoptimized designs. The optimized exterior wall heat transfer coefficient (K-value) is 0.592 W/(m^2·K), with a thermal inertia index (D-value) of 5.061; the roof K-value is 0.336 W/(m^2·K), with a D-value of 3.512. Compared to before optimization, the exterior wall K-value decreased by 0.156 W/(m^2·K), and the D-value decreased by 1.263; the roof K-value decreased by 0.024 W/(m^2·K), and the D-value decreased by 0.852. The optimized thermal performance of both exterior walls and roofs meets the specific requirements regarding K-values and D-values stipulated in Shenzhen's Standard "Energy Efficiency Design Standard for Public Buildings" SJG 44-2025.

Concerning carbon emissions, after optimization, the exterior wall emits 83,913.5 kg of CO_2, while the roof emits 29,526.4 kg. Compared to before optimization, CO_2 emissions from the exterior wall were reduced by 19,228 kg, and the roof by 7,280.4 kg. The reduction rates are 18.6% for the exterior wall and 19.8% for the roof, indicating significant reductions in carbon emissions under the premise of meeting thermal performance requirements.

In terms of costs, after optimization, the exterior wall costs RMB 695,400, and the roof costs RMB 1,641,730.8. Compared to the pre-optimization costs of

RMB 719,150 for the exterior wall and RMB 1,722,746 for the roof, the exterior wall cost was reduced by RMB 23,750, and the roof cost by RMB 81,015.2. The exterior wall cost decreased by 3.3%, and the roof cost by 4.7%. The optimized scheme achieved the lowest cost while ensuring building thermal performance and minimizing carbon emissions, demonstrating the feasibility and effectiveness of multi-objective optimization design in building economics and sustainability.

Through multi-objective optimization design, this study not only enhanced the thermal performance of suburban buildings but also significantly reduced carbon emissions and costs, providing strong technical support and practical reference for the sustainable development of suburban buildings.

5.2 Prospects

While this study yields substantial results, further research directions in multi-objective optimization for sustainable building envelopes include:

Smart dynamic-response technologies:

Explore applications like intelligent insulation materials and photochromic glass to enable automatic performance adjustments based on indoor/outdoor conditions, enhancing energy efficiency and comfort [38].

Interdisciplinary integration:

Combine architecture, materials science, energy science, and environmental science to improve envelope performance holistically, from microscopic material structures to macroscopic building behavior.

Life-cycle cost-benefit analysis:

Incorporate costs across all phases (construction, operation, maintenance, retrofitting, and demolition) to refine decision-making for long-term economic and sustainability outcomes.

Climate resilience:

Investigate envelope adaptability to extreme weather (e.g., heatwaves, heavy rain, strong winds) to ensure safety and stability under climate change.

User behavior integration:

Study how occupant behavior influences envelope performance and incorporate these insights into optimization to enhance user satisfaction and operational efficiency.

Advancing these areas will drive innovation in sustainable building envelopes, offering stronger technical support for the construction industry's green transition and low-carbon transformation.

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APPENDIX A ANTIPLAGIARISM CHECK REPORT

ПРОТОКОЛ ПЕРЕВІРКИ КВАЛІФІКАЦІЙНОЇ РОБОТИ

Назва роботи: Багатокритеріальна оптимізація у проєктуванні огороджувальних конструкцій для сільських/приміських районів з урахуванням сталого розвитку. / Multicriteria-optimised design of sustainable envelopes for rural/suburb areas

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 1,91 %

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)

Здобувач 徐翠媚 (підпис) Сюй Цуймен /Xu Cuimei, ст.гр.2Б-23м (прізвище, ініціали, посада)

APPENDIX B MATLAB WALL ROOF OPTIMISATION LISTING

```
function WallRoofOptimization()
    % === Parameter Definition ===
    % Wall Parameters
    S_wall = 950;    % Wall area (m²)
    wall_layers = {
        [0.025, 0.030],    % M20 Cement Mortar (25mm or 30mm)
        [0.20, 0.25],      % Aerated Concrete Block (200mm or 250mm)
        [0.02, 0.030],     % Perlite Insulation Mortar (20mm or 30mm)
        [0.030, 0.035]     % M20 Plastering Mortar (30mm or 35mm)
    };
    lambda_wall = [0.930, 0.220, 0.080, 0.085];      % Thermal Conductivity
(W/m·K)
    S_wall_layers = [11.370, 4.286, 1.754, 1.190];     % Thermal Capacity
(W/m²·K)
    C_wall = [266, 336, 154, 380];                    % Carbon Emission Factor
(kg/m³)
    cost_wall = {
        [28.00, 43.05],     % M20 Cement Mortar (RMB/m²)
        [632, 650],          % Aerated Concrete Block (RMB/m²) Corrected unit
error
        [42, 47],            % Perlite Insulation Mortar (RMB/m²)
        [30, 32]             % M20 Plastering Mortar (RMB/m²)
    };

    % Roof Parameters (Corrected unit error)
    S_roof = 391;    % Roof area (m²)
    roof_layers = {
        [0.020, 0.030],    % M20 Cement Mortar (20mm or 30mm)
        [0.040, 0.050],    % C25 Fine Aggregate Concrete (40mm or 50mm)
        [0.005, 0.010],    % Waterproof Mortar (5mm or 10mm)
        [0.030, 0.040],    % C20 Fine Aggregate Concrete (30mm or 40mm)
        [0.080, 0.100],    % Extruded Polystyrene Board (80mm or 100mm)
        [0.150, 0.200]     % Reinforced Concrete (150mm or 200mm)
    };
    lambda_roof = [0.930, 1.510, 0.930, 1.740, 0.030, 1.740];   % Thermal
Conductivity
    S_roof_layers = [11.370, 15.245, 11.306, 17.200, 0.384, 17.200]; % Thermal
Capacity
    C_roof = [266, 295, 365, 288, 46, 295];                        % Carbon
Emission Factor
    cost_roof = {
        [20.00, 28.00],    % M20 Cement Mortar (RMB/m²)
        [350, 400],         % C25 Fine Aggregate Concrete (RMB/m²) Corrected
unit error
        [50, 55],           % Waterproof Mortar (RMB/m²)
```

```
        [300, 400],          % C20 Fine Aggregate Concrete (RMB/m²) Corrected
unit error
        [128.8, 136],        % Extruded Polystyrene Board (RMB/m²)
        [3350, 3500]         % Reinforced Concrete (RMB/m²) Corrected unit error
    };

    % Update Design Benchmark Unit Prices
    design_cost_wall = [28.00, 650, 47, 32];
    design_cost_roof = [20.00, 400, 50, 300, 136, 3500];

    % Define Design Scheme Thickness
    design_wall = [0.025, 0.250, 0.030, 0.035];
    design_roof = [0.020, 0.050, 0.005, 0.030, 0.100, 0.200];

    % === Wall Optimization ===
    [g1, g2, g3, g4] = ndgrid(1:2, 1:2, 1:2, 1:2);
    combinations_wall = [g1(:), g2(:), g3(:), g4(:)];
    valid_solutions_wall = [];
    Ri_wall = 0.11;
    Re_wall = 0.04;

    for i = 1:size(combinations_wall, 1)
        d = [wall_layers{1}(combinations_wall(i,1)), ...
             wall_layers{2}(combinations_wall(i,2)), ...
             wall_layers{3}(combinations_wall(i,3)), ...
             wall_layers{4}(combinations_wall(i,4))];

        % Constraint 1: Total thickness ≤ 0.35m
        if sum(d) > 0.35
            continue;
        end

        % Calculate thermal resistance and K value
        R = d ./ lambda_wall;
        R_total = Ri_wall + sum(R) + Re_wall;
        K = 1 / R_total;

        % Calculate thermal inertia index D
        D = sum(S_wall_layers .* R);

        % Constraint 2: Corrected thermal performance judgment
        if (D > 2.5 && K > 0.8) || (D <= 2.5 && K > 1.5)
            continue;
        end

        % Calculate carbon emissions and cost
        CO2 = S_wall * sum(d .* C_wall);
```

```
    cost = 0;
    for j = 1:4
        cost = cost + S_wall * cost_wall{j}(combinations_wall(i,j));
    end
    Cost = cost;

    valid_solutions_wall = [valid_solutions_wall; d, K, D, CO2, Cost];
end

% === Roof Optimization ===
[g1, g2, g3, g4, g5, g6] = ndgrid(1:2, 1:2, 1:2, 1:2, 1:2, 1:2);
combinations_roof = [g1(:), g2(:), g3(:), g4(:), g5(:), g6(:)];
valid_solutions_roof = [];
Ri_roof = 0.11;
Re_roof = 0.04;

for i = 1:size(combinations_roof, 1)
    d = [roof_layers{1}(combinations_roof(i,1)), ...
         roof_layers{2}(combinations_roof(i,2)), ...
         roof_layers{3}(combinations_roof(i,3)), ...
         roof_layers{4}(combinations_roof(i,4)), ...
         roof_layers{5}(combinations_roof(i,5)), ...
         roof_layers{6}(combinations_roof(i,6))];

    % Constraint 1: Total thickness ≤ 0.40m
    if sum(d) > 0.40
        continue;
    end

    % Calculate thermal resistance and K value
    R = d ./ lambda_roof;
    R_total = Ri_roof + sum(R) + Re_roof;
    K = 1 / R_total;

    % Calculate thermal inertia index D
    D = sum(S_roof_layers .* R);

    % Constraint 2: Corrected thermal performance judgment
    if (D > 2.5 && K > 0.5) || (D <= 2.5 && K > 0.8)
        continue;
    end

    % Calculate carbon emissions and cost
    CO2 = S_roof * sum(d .* C_roof);
    cost = 0;
    for j = 1:6
        cost = cost + S_roof * cost_roof{j}(combinations_roof(i,j));
```

```
            end
            Cost = cost;

            valid_solutions_roof = [valid_solutions_roof; d, K, D, CO2, Cost];
        end

        % === Output Results ===
        if isempty(valid_solutions_wall) || isempty(valid_solutions_roof)
            error('No feasible solution found, please check constraints or parameter settings');
        else
            % Sort by Cost to find the optimal solution
            [~, idx_wall] = sortrows(valid_solutions_wall, 8);
            optimal_wall = valid_solutions_wall(idx_wall(1), :);

            [~, idx_roof] = sortrows(valid_solutions_roof, 10);
            optimal_roof = valid_solutions_roof(idx_roof(1), :);

            % Output Wall Optimal Solution
            fprintf('Wall Optimal Solution:\n');
            fprintf('M20 Cement Mortar Thickness: %.3f m\n', optimal_wall(1));
            fprintf('Aerated Concrete Block Thickness: %.3f m\n', optimal_wall(2));
            fprintf('Perlite Insulation Mortar Thickness: %.3f m\n', optimal_wall(3));
            fprintf('M20 Plastering Mortar Thickness: %.3f m\n', optimal_wall(4));
            fprintf('K=%.3f W/m²K, D=%.3f, CO2=%.1f kg, Cost=%.1f RMB\n\n', optimal_wall(5:8));

            % Output Roof Optimal Solution
            fprintf('Roof Optimal Solution:\n');
            fprintf('M20 Cement Mortar Thickness: %.3f m\n', optimal_roof(1));
            fprintf('C25 Fine Aggregate Concrete Thickness: %.3f m\n', optimal_roof(2));
            fprintf('Waterproof Mortar Thickness: %.3f m\n', optimal_roof(3));
            fprintf('C20 Fine Aggregate Concrete Thickness: %.3f m\n', optimal_roof(4));
            fprintf('Extruded Polystyrene Board Thickness: %.3f m\n', optimal_roof(5));
            fprintf('Reinforced Concrete Thickness: %.3f m\n', optimal_roof(6));
            fprintf('K=%.3f W/m²K, D=%.3f, CO2=%.1f kg, Cost=%.1f RMB\n\n', optimal_roof(7:10));
        end

        % === Plotting Function ===
        PlotOptimizationResults(optimal_wall, optimal_roof, S_wall, S_roof, ...
            wall_layers, lambda_wall, S_wall_layers, C_wall, cost_wall, ...
            roof_layers, lambda_roof, S_roof_layers, C_roof, cost_roof, ...
            design_wall, design_roof, design_cost_wall, design_cost_roof);
```

```
end

function PlotOptimizationResults(optimal_wall, optimal_roof, S_wall, S_roof, ...
    wall_layers, lambda_wall, S_wall_layers, C_wall, cost_wall, ...
    roof_layers, lambda_roof, S_roof_layers, C_roof, cost_roof, ...
    design_wall, design_roof, design_cost_wall, design_cost_roof)

    % Convert thicknesses to mm for plotting
    design_wall_mm = design_wall * 1000;
    optimal_wall_mm = optimal_wall(1:4) * 1000;
    design_roof_mm = design_roof * 1000;
    optimal_roof_mm = optimal_roof(1:6) * 1000;

    % Calculate Design Scheme Indicators
    % Wall
    R_wall_design = design_wall ./ lambda_wall;
    R_total_wall_design = 0.11 + sum(R_wall_design) + 0.04;
    K_wall_design = 1 / R_total_wall_design;
    D_wall_design = sum(S_wall_layers .* R_wall_design);
    CO2_wall_design = S_wall * sum(design_wall .* C_wall);
    cost_wall_design = 0;
    for j = 1:4
        cost_wall_design = cost_wall_design + S_wall * design_cost_wall(j);
    end

    % Roof
    R_roof_design = design_roof ./ lambda_roof;
    R_total_roof_design = 0.11 + sum(R_roof_design) + 0.04;
    K_roof_design = 1 / R_total_roof_design;
    D_roof_design = sum(S_roof_layers .* R_roof_design);
    CO2_roof_design = S_roof * sum(design_roof .* C_roof);
    cost_roof_design = 0;
    for j = 1:6
        cost_roof_design = cost_roof_design + S_roof * design_cost_roof(j);
    end

    % Optimized Scheme Indicators
    % Wall
    R_wall_optimized = optimal_wall(1:4) ./ lambda_wall;
    R_total_wall_optimized = 0.11 + sum(R_wall_optimized) + 0.04;
    K_wall_optimized = 1 / R_total_wall_optimized;
    D_wall_optimized = sum(S_wall_layers .* R_wall_optimized);
    CO2_wall_optimized = S_wall * sum(optimal_wall(1:4) .* C_wall);
    cost_wall_optimized = optimal_wall(8);

    % Roof
    R_roof_optimized = optimal_roof(1:6) ./ lambda_roof;
```

```
R_total_roof_optimized = 0.11 + sum(R_roof_optimized) + 0.04;
K_roof_optimized = 1 / R_total_roof_optimized;
D_roof_optimized = sum(S_roof_layers .* R_roof_optimized);
CO2_roof_optimized = S_roof * sum(optimal_roof(1:6) .* C_roof);
cost_roof_optimized = optimal_roof(10);

% === Plot Comparison Graphs ===

% --- Figure 1: Wall Material Thickness Comparison ---
figure('Name', 'Design vs Optimized Wall Material Thickness', 'Position', [100,
100, 800, 600]);
bar([design_wall_mm; optimal_wall_mm]', 'Grouped');
hold on;
set(gca, 'XTickLabel', {'M20 Cement Mortar', 'Aerated Concrete', 'Perlite
Insulation', 'M20 Plastering'}, 'FontSize', 8);
legend('Design', 'Optimized', 'Location', 'best');
title('Design vs Optimized Wall Material Thickness');
xlabel('Material Layers');
ylabel('Thickness (mm)');
grid on;
hold off;

% --- Figure 2: Roof Material Thickness Comparison ---
figure('Name', 'Design vs Optimized Roof Material Thickness', 'Position', [100,
100, 800, 600]);
bar([design_roof_mm; optimal_roof_mm]', 'Grouped');
hold on;
set(gca, 'XTickLabel', {'M20 Cement Mortar', 'C25 Fine Aggregate Concrete',
'Waterproof Mortar', ...
    'C20 Fine Aggregate Concrete', 'Extruded Polystyrene Board', 'Reinforced
Concrete'}, 'FontSize', 8);
legend('Design', 'Optimized', 'Location', 'best');
title('Design vs Optimized Roof Material Thickness');
xlabel('Material Layers');
ylabel('Thickness (mm)');
grid on;
hold off;

% --- Figure 3: K/D Values Comparison ---
figure('Name', 'Design vs Optimized K/D Values', 'Position', [100, 100, 800,
600]);

% Wall K/D Comparison
subplot(2, 1, 1);
bar([K_wall_design, K_wall_optimized; D_wall_design, D_wall_optimized],
'Grouped');
hold on;
```

```
set(gca, 'XTickLabel', {'Design', 'Optimized'}, 'FontSize', 8);
legend('K Value', 'D Value', 'Location', 'best');
title('Wall K/D Values Comparison');
xlabel('Scheme');
ylabel('Value');
grid on;
hold off;

% Roof K/D Comparison
subplot(2, 1, 2);
bar([K_roof_design, K_roof_optimized; D_roof_design, D_roof_optimized],
'Grouped');
hold on;
set(gca, 'XTickLabel', {'Design', 'Optimized'}, 'FontSize', 8);
legend('K Value', 'D Value', 'Location', 'best');
title('Roof K/D Values Comparison');
xlabel('Scheme');
ylabel('Value');
grid on;
hold off;

    % --- Figure 4: CO2 Values Comparison ---
figure('Name', 'Design vs Optimized CO2 Values', 'Position', [100, 100, 800,
600]);
CO2_data = [CO2_wall_design, CO2_wall_optimized; CO2_roof_design,
CO2_roof_optimized];
h = bar(CO2_data, 'grouped');
  h(1).FaceColor = [0, 0.4470, 0.7410];
h(2).FaceColor = [0.8500, 0.3250, 0.0980];
set(gca, 'XTickLabel', {'Wall', 'Roof'}, 'FontSize', 10);
legend({'Design', 'Optimized'}, 'Location', 'best');
title('Design vs Optimized CO2 Emissions');
xlabel('Components');
ylabel('CO2 Emissions (kg)');
grid on;

% --- Figure 5: Cost Values Comparison ---
figure('Name', 'Design vs Optimized Cost Values', 'Position', [100, 100, 800,
600]);
Cost_data = [cost_wall_design, cost_wall_optimized; cost_roof_design,
cost_roof_optimized];
h = bar(Cost_data, 'grouped');
h(1).FaceColor = [0, 0.4470, 0.7410];
h(2).FaceColor = [0.8500, 0.3250, 0.0980];
set(gca, 'XTickLabel', {'Wall', 'Roof'}, 'FontSize', 10);
legend({'Design', 'Optimized'}, 'Location', 'best');
title('Design vs Optimized Cost Comparison');
```

```
        xlabel('Components');
        ylabel('Cost (RMB)');
        grid on;
        hold off;

        % Display Detailed Indicators of Design and Optimized Solutions
        disp('=== Design Scheme Indicators ===');
        fprintf('Wall: K=%.3f, D=%.3f, CO2=%.1f kg, Cost=%.1f RMB\n', K_wall_design, D_wall_design, CO2_wall_design, cost_wall_design);
        fprintf('Roof: K=%.3f, D=%.3f, CO2=%.1f kg, Cost=%.1f RMB\n\n', K_roof_design, D_roof_design, CO2_roof_design, cost_roof_design);

        disp('=== Optimized Scheme Indicators ===');
        fprintf('Wall: K=%.3f, D=%.3f, CO2=%.1f kg, Cost=%.1f RMB\n', K_wall_optimized, D_wall_optimized, CO2_wall_optimized, cost_wall_optimized);
        fprintf('Roof: K=%.3f, D=%.3f, CO2=%.1f kg, Cost=%.1f RMB\n', K_roof_optimized, D_roof_optimized, CO2_roof_optimized, cost_roof_optimized);
    end
```

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Professor BIKS Yuriy, for the invaluable guidance and support throughout this research. Your expertise and rigorous academic approach have greatly inspired me and been instrumental in shaping this study.

I am also grateful to the experts and professors who reviewed this project. Your insightful comments and suggestions have been crucial in refining and enhancing the project's quality.

Special thanks are due to the partnering enterprises involved in the XA project for their material and technical support, which provided a solid foundation for the research.

Additionally, I thank my family and friends for their constant encouragement and understanding, which have been my driving force during this research.

This project, as a near-zero-energy public building demonstration in Shenzhen's suburban area, aims to advance green building and support the dual carbon strategy. I hope the findings will contribute to Shenzhen's sustainable development and the green transformation of China's construction industry.

Multicriteria-optimised design of sustainable envelopes for suburb areas

- **Student name:** XU Cuimel
- **University:** Vinnytsia National Technical University
- **Supervisor's name:** BIKS Yuriy

- **Date:** June 19.2025

CONTENTS

Research background

Research background

1.1 High Energy Consumption and Environmental Impact of Buildings

Buildings significantly impact the environment through energy use and carbon emissions. The construction phase generates substantial waste (300–500 tons per 10,000 m^2) and accounts for 20–30% of a building's lifecycle carbon emissions. During operation, heating, cooling, and lighting dominate energy use, exacerbating urban heat islands and greenhouse gas emissions.

1.2 China’s Commitment to Sustainable Development

The Chinese government has implemented policies like the Green Building Evaluation Standard (2006) and the 14th Five-Year Plan for Building Energy Saving (2021), aligning with its "3060" dual-carbon goals (peak emissions by 2030, neutrality by 2060). These policies drive energy-efficient designs but often focus narrowly on urban areas.

Research background

1.3 Neglected Challenges in Suburban Areas

Suburban buildings, while adhering to energy standards, frequently overlook lifecycle carbon emissions and cost-effectiveness. Traditional designs prioritize thermal performance alone, lacking integrated optimization. This gap highlights the need for multicriteria approaches balancing energy efficiency, carbon reduction, and affordability.

1.4 Conclusion

Given these challenges, multicriteria-optimised design of sustainable envelopes for suburb areas is critical to advancing holistic, low-carbon suburban development.

Project Case

Project Case

2.1 Project Overview

Location: Suburban of Bao'an District, Shenzhen

Type: Near Zero Energy Consumption (nZEB) Demonstration Public Building

Area: 1276 m^2

Function: Information service, leisure area, catering, retail, office

Certification: China Green Building Two Star Standard (GB/T 50378-2019)

Project Case

2.1 Project Design

The floor plans for Levels 1, 2, 3, and the roof are shown in Figures 2.1, 2.2, 2.3, 2.4, and 2.5, respectively.

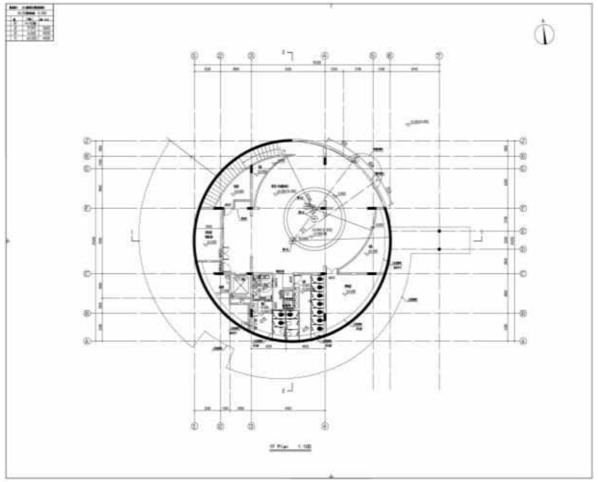

Figure 2.1 1F plan

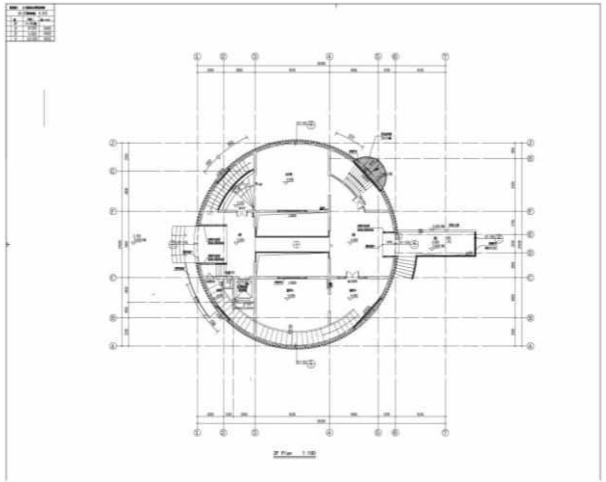

Figure 2.2 2F plan

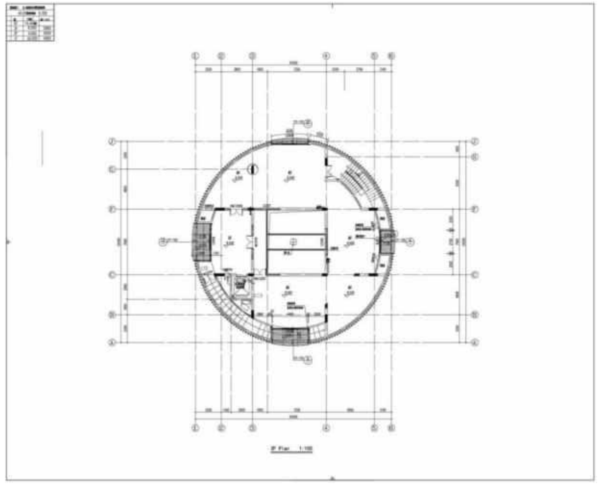

Figure2.3 3F plan

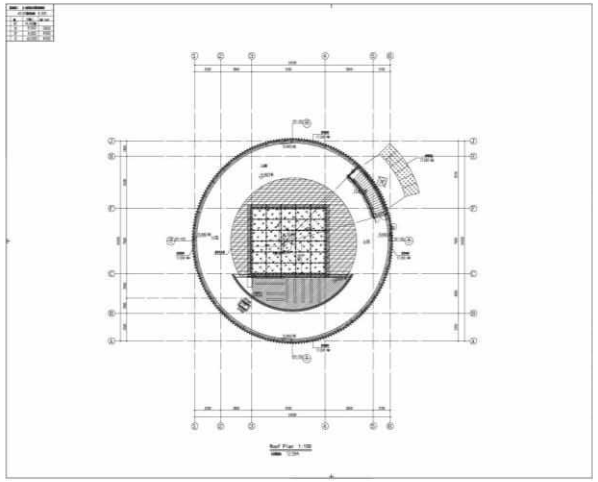

Figure2.4 Roof plan

Project Case

2.1 Project Design

Figure2.5 Project construction photos

Figure2.6 Realistic pictures of the project

Problem statement/Objective

Problem statement/Objective

3.1 Problem Statement

Suburban sustainable building design often prioritizes energy-saving standards but overlooks carbon emissions and construction costs during the design phase.

Traditional single-objective optimization approaches fail to balance thermal performance, carbon footprint, and economic efficiency holistically.

There is a lack of systematic design frameworks tailored to suburban climatic conditions and functional requirements.

Problem statement/Objective

3.2 Research Objectives

Develop a multi-objective optimization framework for sustainable building envelopes in suburban areas, integrating thermal performance, life-cycle carbon emissions, and cost control.

Apply the NSGA-II algorithm via Matlab to optimize envelope material thicknesses for the XA near-zero-energy project in Shenzhen’s suburbs.

Validate the framework through case studies to enhance energy efficiency, reduce carbon emissions, and improve cost-effectiveness in suburban construction.

Provide theoretical guidance and practical references for green building development in suburban regions.

Methodology

Methodology

4.1 Multi-Objective Optimisation Framework

Objectives： Minimize thermal transmittance (K-value), carbon emissions, and construction cost.

Constraints： Wall thickness ≤ 0.35m, roof thickness ≤ 0.4m, and thermal performance standards (e.g., K-value and thermal inertia index D).

Reference: Technical route diagram of the optimization process as Figure 4.1

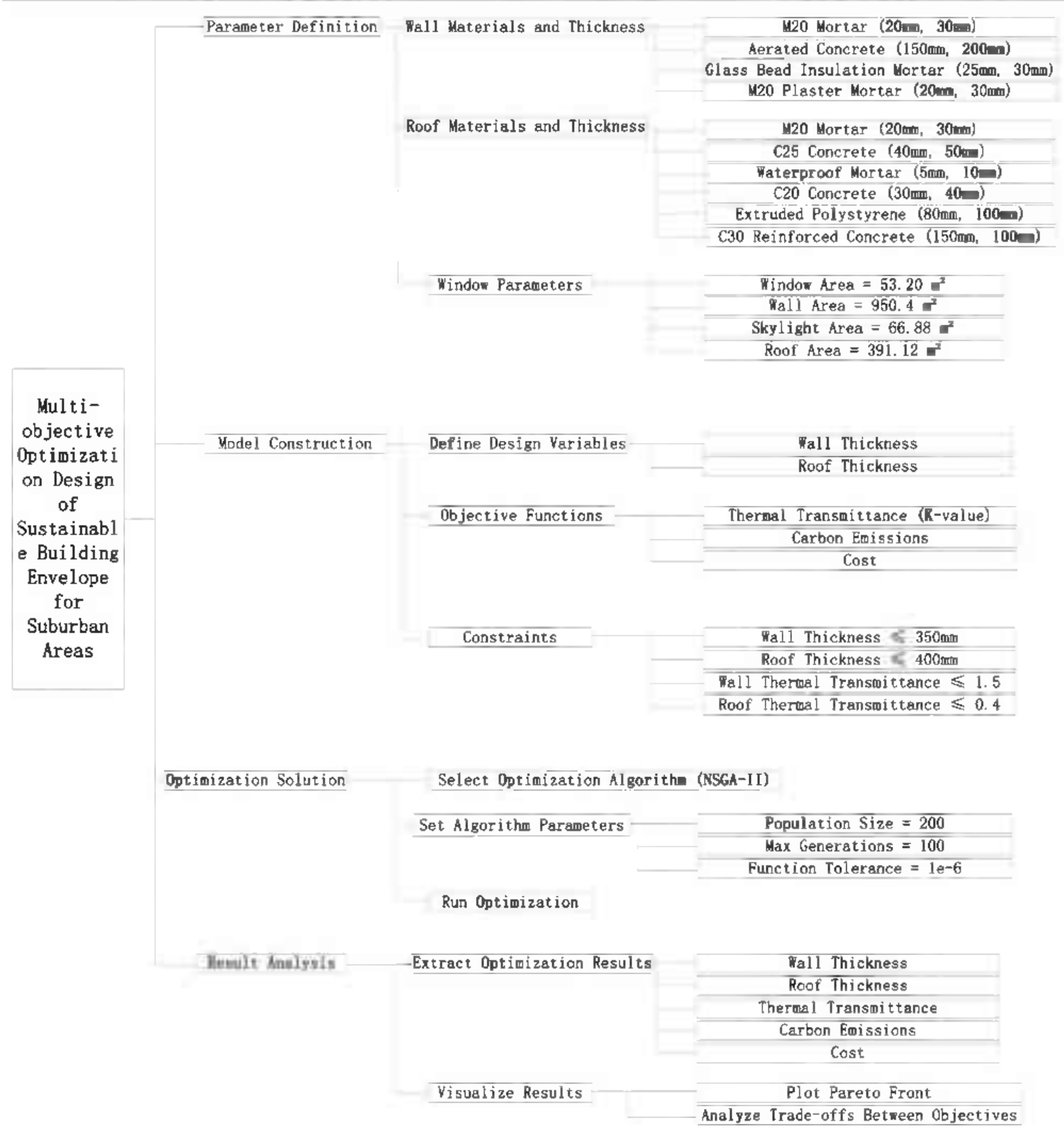

Figure 4.1 Technical route diagram of the optimization process

4.2 NSGA-II Algorithm Implementation

Reserch Tool:MATLAB with Global Optimization Toolbox.

Key Parameters: Population size = 200, maximum iterations = 100, non-dominated sorting for Pareto front generation.

Advantage: Efficiently balances conflicting objectives (e.g., thermal performance vs. cost).

4.3 Material Thickness Optimization

Variables: Thicknesses of wall/roof materials (e.g., aerated concrete, XPS board)

Model Design: Combinations of material layers tested via exhaustive search (e.g., 2^4 wall layers and 2^6 roof layers)

The types and thicknesses of the materials used for the walls and roof are shown in Table 4.1 and Figure 4.2-1、Figure 4.2-2.

Methodology

Table 4.1 Wall Material Types and Thickness Specifications

Category (Component)	**Parameter (Material type)**	**Variable type**	**Thickness options(mm)**
Exterior wall	Cement mortar	Discrete	20、30
	Aerated concrete		150、200
	Vitrified microsphere insulation mortar		25、30
	M20 Plastering mortar		20、30
Roof	Cement mortar	Discrete	20、30
	C25 Fine-aggregate concrete		40、50
	Waterproof mortar		5、10
	C20 Fine-aggregate concrete		30、40
	XPS board(ρ=25-32)		80、100
	Reinforced concrete		100、150

Note： Since the windows, doors, and skylights of this project use an aluminum frame structure with 6 Low-E s + 12A + 6, which already meets the project's energy-saving and daylighting requirements, this study does not consider them as subjects for further optimization research.

Methodology

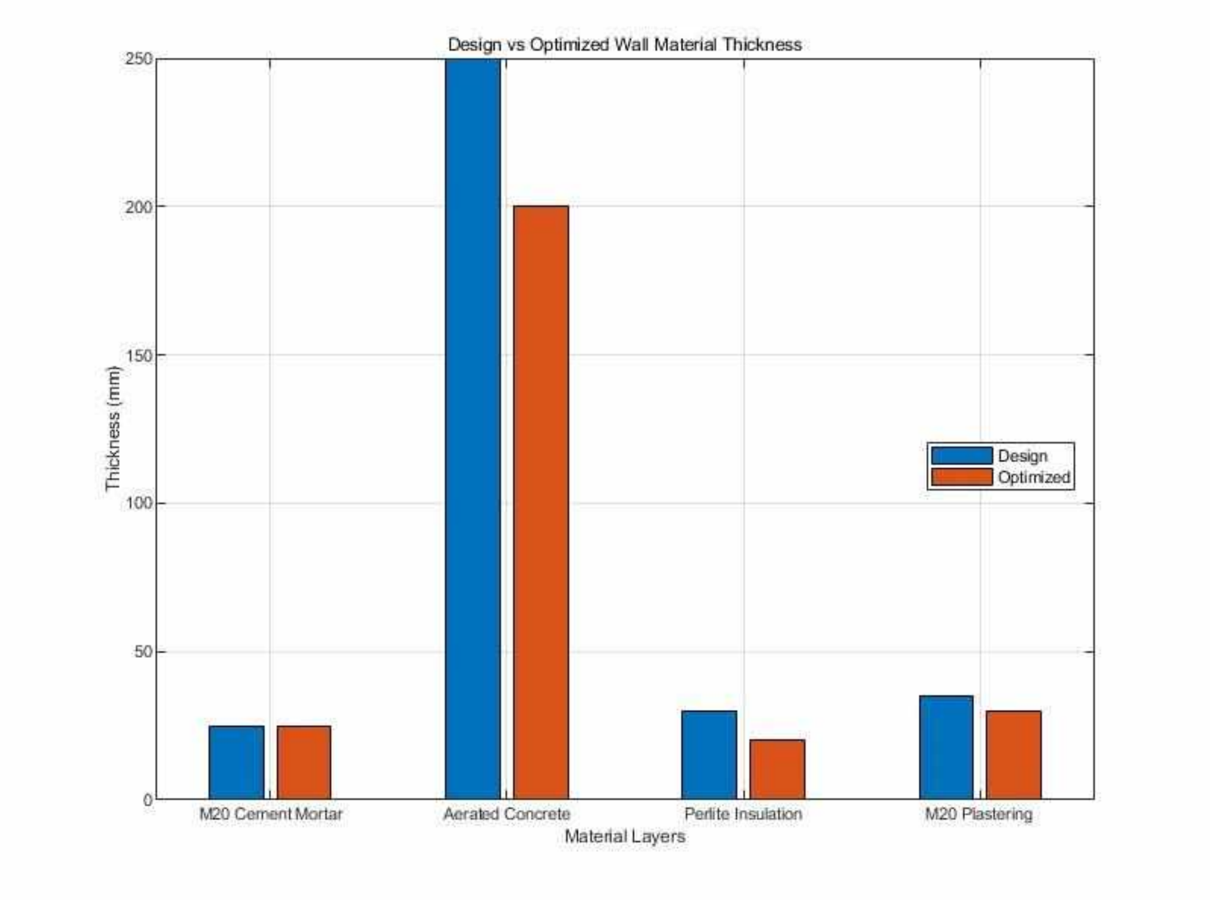

Figure 4.1 – Comparison chart of the thicknesses of each material layer in the wall.

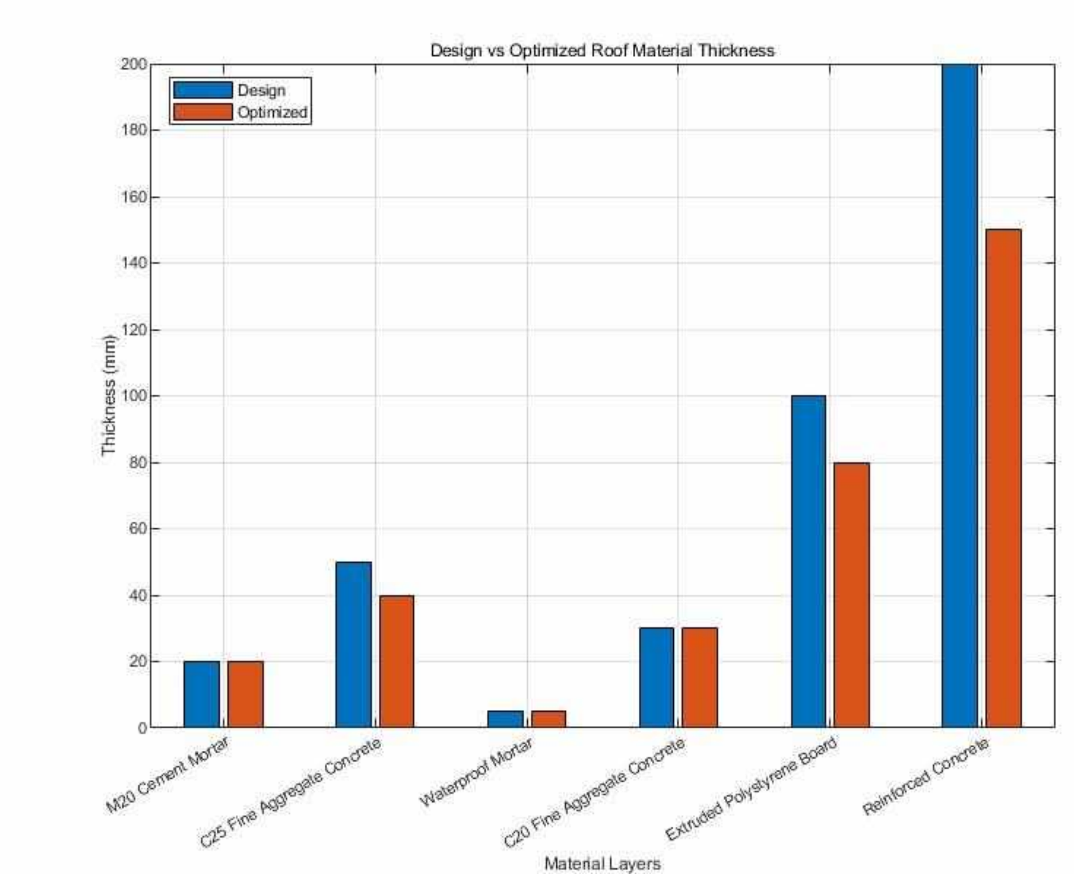

Figure 4.2 – Comparison chart of the thicknesses of each material layer in the roof.

Methodology

4.4 Thermal Performance Metrics

K-value: Reduced by 0.156 W/(m²·K) for walls and 0.02 W/(m²·K) for roofs post-optimization.

D-value: Decreased by 1.263 for walls and 0.852 for roo meeting regional thermal standards.

Reference: Figure 4.3 K/D value comparison chart .

Conclusion: The thickness of the wall has decreased, but the K value has also decreased, and the energy-saving effect has been improved

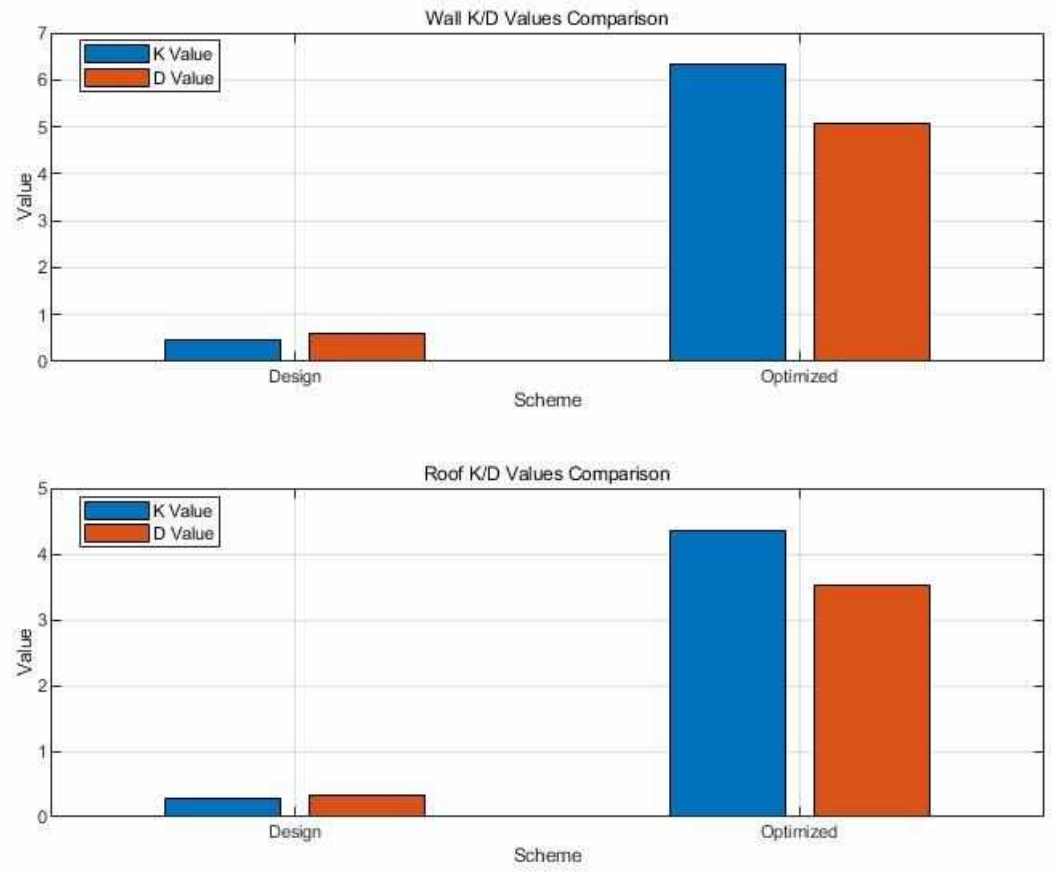

Figure 4.3 – Comparison chart of K-values and D-values for walls and roofs.

Methodology

4.5 Carbon Emission Reduction

Results: The exterior wall emits 83,913.5 kg of CO_2, while the roof emits 29,526.4 kg. Compared to before optimization, CO_2 emissions from the exterior wall were reduced by 19,228 kg, and the roof by 7,280.4 kg. The reduction rates are 18.6% for the exterior wall and 19.8% for the roof.

Mechanism: Low-carbon material selection (e.g., XPS board) and thickness optimization.

Reference: Figure 4.4 CO_2 emission comparison chart .

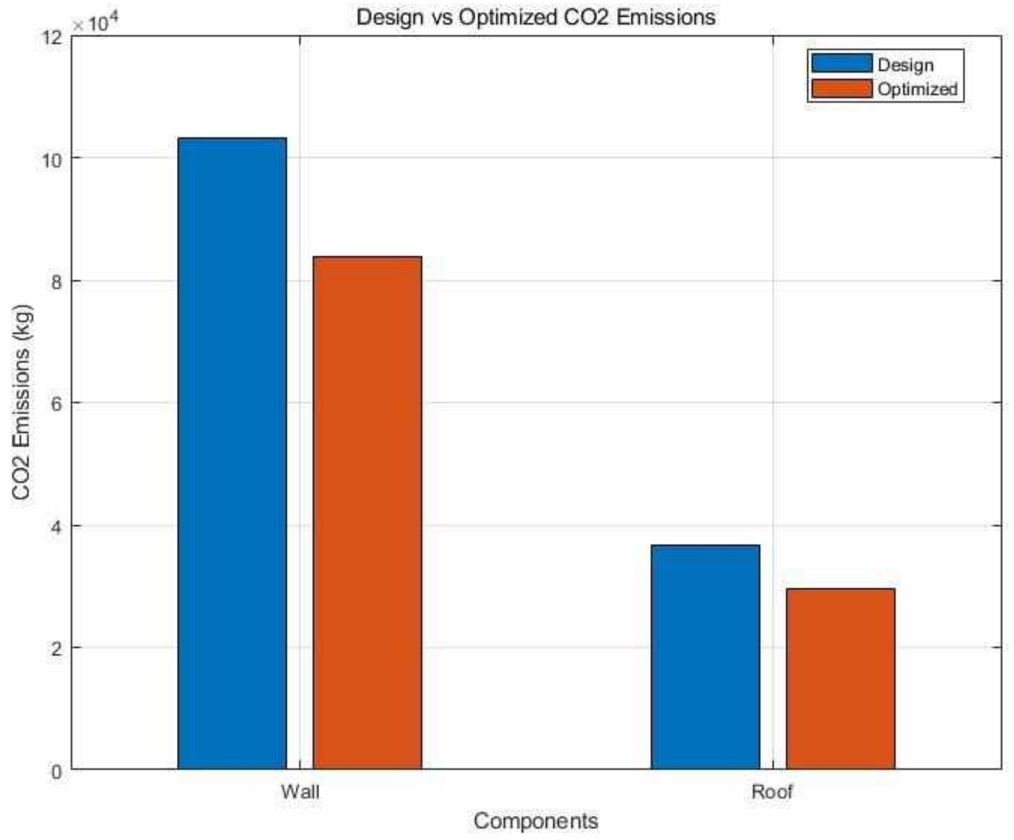

Figure 4.4 – Comparison chart of CO_2 emissions for walls and roofs

Methodology

4.6 Cost Optimization

Cost Savings: Wall cost reduced by 3.3%, roof cost by 4.7%.

Strategy: Balancing high-performance materials with cost-effective thicknesses.

Reference: Figure 3.5 cost comparison chart （design vs. optimized values）.

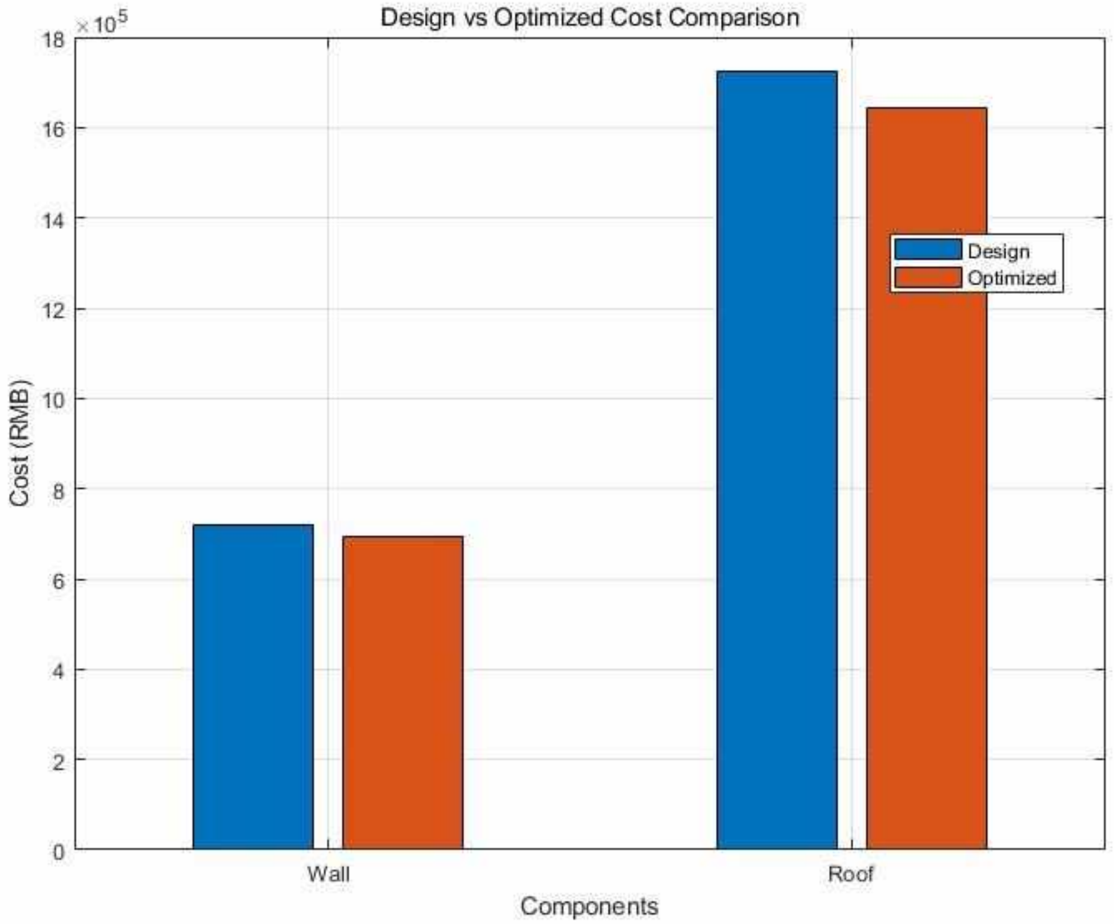

Figure 3.5: Comparison chart of costs for walls and roofs.

After optimization, the exterior wall costs RMB 695,400, and the roof costs RMB 1,641,730.8. Compared to the pre-optimization costs of RMB 719,150 for the exterior wall and RMB 1,722,746 for the roof, the exterior wall cost was reduced by RMB 23,750, and the roof cost by RMB 81,015.2.

Discussion

Discussion

5.1 Theoretical Contribution

Developed a multi-objective optimization framework integrating thermal performance, carbon emissions, and cost, addressing the gap in traditional single-objective designs.

We tested the model on one building to save energy.

5.2 Comparison with Existing Research

Domestic studies: Most focus on single performance metrics (e.g., thermal insulation), while this study emphasizes holistic optimization.

International practices: Aligns with European Passivhaus standards but adapts to suburban China’s climatic and economic contexts (e.g., lower-cost materials like aerated concrete).

Novelty: Combines Life Cycle Carbon Footprint theory with building thermal science, enabling lifecycle sustainability assessment.

Discussion

5.3 Practical Implications

Energy efficiency: Reduced K-values by 0.156–0.024 $W/(m^2 \cdot K)$, meeting China's Green Building Two-Star certification.

Carbon reduction: 18.6–19.8% emission cuts, supporting China's "3060" dual-carbon target.

Cost-effectiveness: 3.3–4.7% cost savings via optimized material thicknesses, balancing performance and economy.

5.4 Limitations

Static optimization: Does not account for dynamic user behavior or climate change impacts.

Material scope: Focused on conventional materials; lacks exploration of emerging smart materials (e.g., phase-change materials).

Geographical specificity: Results are optimized for Shenzhen's subtropical climate, requiring regional adaptation for other zones.

Conclusions

Conclusion

6.1 Methodological Validation

The multi-objective optimization framework, integrating NSGA-II algorithm and MATLAB simulation, successfully balances thermal performance, carbon emissions, and cost. The optimized results (e.g., K-value reductions and carbon savings) align with China's green building standards, verifying the approach's effectiveness.

6.2 Support for Suburban Sustainable Development

The study provides tangible design strategies for suburban envelopes, such as material thickness optimization and low-carbon material selection. These strategies enhance energy efficiency (e.g., 18.6% carbon reduction for walls) and cost-effectiveness, addressing the unique climatic and economic needs of suburban areas.

6.3 Theoretical and Practical Contributions

A novel integrated model for suburban contexts, bridging traditional single-objective design limitations.

A case study-driven reference for policymakers and practitioners, promoting scalable green construction practices in transitional urban-rural zones.

Further research / Acknowledgements

Further research / Acknowledgements

7.1 Addressing Research Limitations

- **Static Optimization：** The current model lacks dynamic factors (e.g., user behavior, seasonal climate changes). Future work should integrate real-time simulation tools (e.g., EnergyPlus) for responsive envelope design.

- **Limited Lifecycle Scope：** Focused on construction-phase emissions, the study needs expansion to full lifecycle analysis (maintenance, demolition) and novel materials (e.g., self-healing concrete).

- **Regional Adaptability：** Validated only for Shenzhen's subtropical climate, the framework requires testing in diverse climatic zones to develop universal guidelines.

Further research / Acknowledgements

7.2 Cutting-Edge Research Directions

- **Smart Envelope Systems：** Develop adaptive technologies (e.g., photochromic glass, phase-change materials) for real-time thermal regulation.

- **Renewable Energy Integration：** Incorporate building-integrated photovoltaics (BIPV) and wind turbines to enhance energy self-sufficiency in suburban buildings.

- **AI-Driven Optimization：** Use machine learning to predict long-term envelope performance degradation and optimize lifecycle cost-effectiveness.

Acknowledgements

I extend sincere gratitude to Vinnytsia National Technical University for fostering my academic growth. Special thanks to Prof. BIKS Yuriy for his meticulous guidance, innovative insights, and unwavering support throughout this research. His expertise in sustainable architecture has been instrumental in shaping the study’s framework and outcomes.

Thank you, respected professors,
for your careful review and valuable guidance.

May peace and good health embrace the world！

SUPERVISOR'S REVIEW
of the Master's Qualification Thesis by Xu Cuimei
on the topic:
"Multicriteria-Optimised Design of Sustainable Envelopes for Suburb Areas"

The Master's qualification thesis presented by Xu Cuimei is dedicated to an urgent and complex problem in the field of sustainable construction—developing and optimising energy-efficient building envelopes for suburban buildings using a multicriteria approach. The work is grounded in modern scientific and regulatory frameworks, particularly the Chinese Green Building Evaluation Standard, and addresses real-world needs in the context of climate-responsive suburban design.

The structure of the thesis is logically built. It includes a comprehensive introduction to theoretical and methodological foundations (Chapters 1–2), a deep case-based analysis of the XA nearly zero-energy public building in Shenzhen (Chapter 3), and a systematic implementation of multi-objective optimisation using MATLAB NSGA-II algorithms (Chapter 4). The fifth chapter outlines conclusions and future research perspectives.

The scientific novelty of the thesis lies in the integrated optimisation of three interdependent objectives: thermal performance, embodied carbon, and lifecycle cost, approached through a customised methodology involving simulation, theoretical modelling, and algorithmic optimisation. The methodology is well-articulated, and the obtained results demonstrate a reduction of up to 19.8% in CO_2 emissions, along with a balanced envelope performance strategy tailored for subtropical suburban climates.

The practical value of the thesis is substantial: the developed framework offers a reference for architectural design offices, planners, and energy consultants interested in low-carbon development. The student demonstrated proficiency in simulation modelling, lifecycle data analysis, and critical reasoning, supported by high-quality visualisations and parametric tables.

However, several aspects require further improvement:

- The economic analysis should be more robust and explicitly formulated as a separate chapter or at least a subsection, including a quantified assessment of expected savings or economic effect.
- All figures, tables, and formulas must be referenced in the main body of the thesis before they appear and follow formatting rules.
- Language clarity and consistency across all sections can be improved.

In conclusion, the thesis of Xu Cuimei meets the requirements for Master's theses in the field of Civil Engineering (Speciality 192), demonstrates sufficient scientific and practical significance, and shows a good level of research autonomy. I recommend the thesis for public defence and assess it at a level of **"A – excellent"**. The author is awarded the qualification "Master of Civil Engineering" in the speciality 192-"Construction and Civil Engineering".

Supervisor:
PhD, Assoc. Prof. *Yuriy BIKS*

Opponent's Review

The Master's Thesis by Xu Cuimei presents a scientifically grounded and methodologically sound approach to the multicriteria optimisation of building envelopes for sustainable construction in suburban areas. The relevance of the topic is unquestionable in light of global climate and energy challenges, especially in rapidly developing urban peripheries.

The thesis integrates thermal performance evaluation, carbon footprint assessment, and cost-efficiency analysis within a unified multi-objective optimisation model, which was implemented using MATLAB. The author successfully applied the NSGA-II genetic algorithm to derive Pareto-optimal solutions for wall and roof design alternatives. The simulation and analytical results are convincing and supported by well-structured data.

The main strengths of the thesis are:

Clear statement of objectives and strong structure.

Integration of climate-specific constraints and building codes.

Application of contemporary tools and methods (LCA, ANN, simulation).

However, I note the following drawbacks:

Lack of visual clarity in charts and some simulation output figures.

Economic calculations need further development and deeper integration with the technical results.

The literature review, although extensive, could benefit from clearer categorisation and critical comparison of methodologies.

In summary, the thesis is innovative and well-executed. It reflects the author's strong analytical approach and research capabilities. I recommend the thesis for defence, and the author, in case of an appropriate defence, will be awarded the qualification "Master of Civil Engineering" in the speciality 192 - "Construction and Civil Engineering" and deserves the grade "excellent" (A).

Opponent:

PhD, Prof. Ivan KOTS