

Article

Theoretical Framework and Research Proposal for Energy Utilization, Conservation, Production, and Intelligent Systems in Tropical Island Zero-Carbon Building

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Abstract: This study aims to theoretically explore the technological systems of tropical island zero-carbon building (TIZCB) to scientifically understand the characteristics of these buildings in terms of energy utilization, energy conservation, energy production, and intelligent system mechanisms. The purpose is to address the inefficiencies and resource wastage caused by the traditional segmented approach to building energy consumption management. Thus, it seeks to achieve a comprehensive understanding and application of the zero-carbon building (ZCB) technology system. This article focuses on the demands for energy-efficient comfort and innovative industrialization in construction. Through an analysis of the characteristics of TIZCB and an explanation of their concepts, it establishes a theoretical framework for examining the system mechanisms of these buildings. Additionally, it delves into the energy utilization, energy conservation, energy production, and intelligent system from macro, meso, and micro perspectives. This approach results in the development of an implementation strategy for studying the mechanisms of energy usage, conservation, and intelligent production systems in TIZCB. The results show that: (1) this study delves into the theoretical underpinnings of TIZCB, emphasizing their evolution from a foundation of low-carbon and near-zero energy consumption. The primary goal is to achieve zero carbon emissions during building operation, with reliance on renewable energy sources. Design considerations prioritize adaptation to high-temperature and high-humidity conditions, integrating regional culture along with the utilization of new materials and technologies. (2) A comprehensive technical framework for TIZCB is proposed, encompassing energy utilization, conservation, production capacity, and intelligent systems. Drawing from systems theory, control theory, and synergy theory, the research employs a macro-meso-micro analytical framework, offering extensive theoretical support for the practical aspects of design and optimization. (3) The research implementation plan establishes parameterized models, unveiling the intricate relationships with building performance. It provides optimized intelligent system design parameters for economically viable zero-carbon operations. This study contributes theoretical and practical support for the sustainable development of TIZCB and aligns with the dual carbon strategy in China and the clean energy free trade zone construction in Hainan.

Keywords: tropical island zero-carbon building (TIZCB); energy utilization–conservation–production; theoretical basis; research framework



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1. Introduction

Reducing greenhouse gas emissions is a crucial step in addressing global climate change [1]. The Paris Agreement is a landmark international accord aimed at addressing climate change and its adverse impacts. The main goal of the agreement is to limit global warming to well below 2 °C above pre-industrial levels, with efforts to limit the temperature increase to 1.5 °C [2]. The Paris Agreement sets a net-zero carbon emission target for the

world, leading the Chinese government to establish a system of achieving peak carbon dioxide emissions by 2030 and carbon neutrality by 2060 [3]. According to the International Energy Agency (IEA), buildings' lifecycle emissions constitute about 39% of global CO₂ emissions, significantly impacting global greenhouse gas contributions. The "14th Five-Year Plan" period is a critical time to implement these dual carbon goals. According to the 2022 China Urban and Rural Construction Carbon Emission Series Research Report [4], China's total building carbon emissions in 2020 were 508 million tCO₂, accounting for 50.9% of the country's total carbon emissions. From 2005 to 2020, national building carbon emissions increased from 223 million tCO₂ to 508 million tCO₂, a 2.3-fold increase with an average annual growth rate of 5.6%. This indicates that energy conservation and carbon reduction in the construction sector are essential for achieving China's dual carbon goals, as continuously growing building carbon emissions pose significant challenges to these targets. China has long promoted building energy efficiency and green buildings, but there is a lack of on-site energy supply methods. The Ministry of Housing and Urban-Rural Development's "the 14th Five Year Plan for Building Energy Conservation and Green Building Development" upgrades traditional "energy conservation and emission reduction" to "energy conservation-production capacity-carbon reduction", providing new technical ideas for ZCBs [5]. The Ministry of Science and Technology and Nine Other Departments' "Implementation Plan for Science and Technology to Support Carbon Peaking and Carbon Neutrality (2022–2030)" calls for focusing on decarbonization, emission reduction, and energy efficiency improvement to promote building energy conservation, emission reduction standards, and whole-process carbon reduction [6]. Tropical island regions in China have long summers without winters and small temperature differences between day and night, resulting in high cooling energy demand for buildings. At the same time, these areas have strong solar radiation capabilities and abundant renewable solar thermal resources. Theoretical exploration of the energy conservation, production capacity, and intelligent system mechanisms of TIZCB has become a key issue supporting the sustainable development of such buildings.

ZCBs, as a novel technological paradigm, have been extensively studied by numerous scholars from diverse perspectives. Moghayedi et al. (2023) [7] evaluated the impact of factors influencing the achievement of net-zero carbon goals on the circular economy based on obstacles and driving forces in employing green technology methods in construction. Scherz et al. (2020) [8] outlined the implementation of system design models during the early design stages of buildings to address the challenges of achieving net-zero carbon building environments. Leung et al. (2018) [9] conducted a study on a ZCB in Hong Kong, analyzing the dissemination of bacterial communities in green building air through the investigation of bacteria's 16S rRNA genes. Bui et al. (2022) [10] comprehensively surveyed the field of zero-carbon renovation in existing buildings, employing a mixed-methods approach to data analysis, revealing evolving hotspots and core research themes. Zhao et al. (2017) [11] developed a conceptual model covering project and organizational aspects to explore the theoretical relationship between business models and ZCBs, aiming to drive sustainable development in the ZCB market. Pan et al. (2014) [12], through a review of zero-carbon village policies and support literature, established a social-technical transformation framework providing information for discussions on current and future zero-carbon emission policies. Girard et al. (2012) [13] argued that the shift towards low-carbon or ZCBs introduces a paradigm shift in energy supply infrastructure, emphasizing the need to understand buildings not only from the demand side but also from the perspective of electricity. Bui et al. (2022) [14] conducted an exploratory study through semi-structured interviews with New Zealand building experts to investigate challenges and issues faced by the New Zealand construction industry in ZCBs. Nidhin et al. (2023) [15] surveyed building stakeholders involved in New Zealand architectural design and construction to understand their awareness of zero-carbon initiatives, providing a practical foundation for the market promotion and policy implementation of ZCBs. Hasan et al. (2023) [16] discussed the legitimacy and legality of implementing net-zero carbon building standards by examining policy

documents from the World Green Building Council. Torriti et al. (2015) [17], drawing on policy framework theory and sociological knowledge, systematically explored the significant challenges in the implementation of zero-carbon residential policies. Walker et al. (2016) [18] reflected on the relationship between politics and governance revealed in the mainstreaming process of abandoning zero-carbon housing in the UK, emphasizing the foundation and positioning of carbon responsibility, and the essential role of the state in achieving daily reproduction of low-carbon living. Lees et al. (2014) [19] investigated the actual use of low-carbon and zero-carbon technologies by housing developers to understand the main drivers and significant roles of ZCB technology choices. Steijger et al. (2013) [20] discussed the constraints of compact urban housing on achieving zero-carbon performance in apartment buildings in the context of the Sustainable Homes Code, highlighting the need for off-site net import of electricity and/or heat. McLeod et al. (2012) [21], through comparative analysis, elucidated the revised definition of zero-carbon housing in the UK and the approaches advocated by the Zero Carbon Hub for policy implementation. In summary, these studies lay the foundation for the theoretical development and practical application of TIZCB. However, these studies primarily focus on macro-level policy implementation, involve fewer specific implementation technical measures, and do not consider the building's intrinsic production capacity from the perspective of the resource endowment of tropical island regions. They lack a comprehensive exploration of the building energy flow system from the perspective of the building integrated system, making it challenging to adapt to industrialized, modular, and integrated pattern innovations and integrated research. Furthermore, they struggle to achieve an effective balance between “zero carbon emissions” and “energy-efficient comfort”.

In summary, there is currently no uniform definition of a ZCB [22]. For example, in the United States, the “National Definition of Zero Emission Buildings: Part 1 Operational Emissions (Version 1.00), Draft Standard” defines a ZCB as highly energy efficient, having no on-site energy use emissions, and being entirely powered by clean energy. In the European Union's “Energy Performance of Buildings Directive”, a ZCB is defined as having very high energy performance, with its very low energy needs fully covered by renewable sources, without any on-site fossil fuel carbon emissions. In the United Kingdom's “Net Zero Carbon Building Framework Definition”, a ZCB is described as high-efficiency, producing or procuring carbon-free renewable energy or high-quality carbon offsets in quantities sufficient to offset annual carbon emissions from building materials and operations. The traditional design approach in tropical island regions emphasizes passive energy conservation as the primary focus and active energy conservation as a secondary consideration [23]. However, TIZCB lack an integrated design that incorporates precise regulation of energy utilization for carbon reduction, energy-efficient building envelopes [24], high-efficiency multi-source energy production [25], and intelligent system integration for carbon reduction [26].

The research gaps mainly manifest as: (1) a lack of unified standard definitions for TIZCB, incomplete technical systems, and immature integrated applications [27]; (2) difficulty in achieving coordinated operation among energy use, energy saving, production capacity, and intelligent systems; and (3) this resulting in the insufficient comprehensive efficiency of zero-carbon operations in tropical island buildings [28].

In light of this, the research objectives of this paper are: (1) to construct a theoretical analysis model based on systems theory, synergy, and control theory by defining the inherent characteristics and technical system of TIZCB. This model will provide theoretical support for the study and optimization of mechanisms and systems related to energy utilization, energy conservation, energy production, and intelligent systems in TIZCB. (2) To establish a quantitative analysis framework for energy utilization, energy conservation, energy production, and intelligent systems from macro, meso, and micro perspectives. In this framework, the macro perspective refers to system decomposition and integration from the perspective of the entire building system of TIZCB; the meso perspective refers to system interaction and coupling from the perspective of energy utilization, energy conservation,

energy production, and intelligent systems in TIZCB; and the micro perspective refers to quantification and regulation from the perspective of design parameters of energy utilization, energy conservation, energy production, and intelligent systems in TIZCB. (3) To form the research logic and implementation plan for the system mechanism of energy utilization, energy conservation, energy production, and intelligent systems in TIZCB. This implementation plan will provide technical support for the practical application and verification analysis of the mechanisms and systems related to energy utilization, energy conservation, energy production, and intelligent systems in TIZCB.

The rest of this paper is organized as follows: in Section 2, based on the introduction of zero carbon architecture and tropical island architecture, TIZCB and their technical system are defined; in Section 3, research methods such as systems theory, control theory, and synergy theory are summarized, and their main roles in this article are introduced; Section 4 develops the theoretical framework for researching integrated energy utilization, conservation, production, and intelligent systems in TIZCB; Section 5 outlines the logical thinking of the research on integrated energy utilization, conservation, production, and intelligent systems in TIZCB; Section 6, in conjunction with the research objectives and major research content, constructs an implementation plan for the study of integrated energy utilization, conservation, production, and intelligent systems in TIZCB; and Section 7 summarizes the research conclusions of this paper.

2. Conceptual Definition

2.1. Zero-Carbon Buildings

ZCBs are developed based on low-carbon buildings and near-ZCBs are developed based on low-carbon buildings, near-zero energy consumption buildings, and zero energy consumption buildings. According to the World Green Building Council [29], a ZCB refers to a building whose carbon emissions during the operation phase are ≤ 0 , and the operating energy comes entirely from renewable sources. Improving building energy efficiency (reducing energy consumption) and optimizing building energy structure (a reduction in fossil fuels and strengthening the application of renewable energy) are important ways to reduce building carbon emissions. According to the announcement of the General Office of the Ministry of Housing and Urban–Rural Development on soliciting public opinions on the draft national standard “Zero Carbon Building Technology Standard (Draft for Comments)”, a ZCB is one that adapts to climate characteristics and site conditions, reduces building energy demand through optimized architectural design while meeting indoor environmental parameters, improves the efficiency of energy equipment and systems, fully utilizes renewable energy and building energy storage, and can combine carbon offset methods such as carbon emission rights trading and green electricity trading on the basis of achieving near-zero carbon buildings, in accordance with Article 3.2.5 or 8.4.7 of this standard [30]. Combining domestic and foreign core definitions of ZCBs, it can be seen that ZCBs advocate the technical principle of “passive priority, active optimization, and balancing of renewable energy”, which aims to eliminate the fossil fuel component in building energy consumption on the basis of reducing energy demand, and can be achieved through the use of local and surrounding renewable energy applications exclusively for their use, as well as financial mechanisms such as carbon trading and green electricity.

2.2. Tropical Island Architecture

Tropical island architecture design aims to adapt to the hot, humid, high-salt, and high-UV tropical island climate environment, reflecting the regional culture and tropical island cultural characteristics of Hainan architecture [31]. It emphasizes the integration of architecture with the ecological environment and urban design, creating open spaces that are accessible to the public through natural ventilation and lighting. At the same time, it actively adopts new materials, technologies, and processes to design and construct outstanding buildings with profound connotations, good functionality, and unique shapes. In terms of China, the biggest difference between tropical island architecture and other

architectural systems lies in the tropical island climate environment. To create assembly-style buildings suitable for tropical island characteristics, the Hainan Provincial Department of Housing and Urban–Rural Development and other departments jointly issued the “Three Year Action Plan for the Development and Improvement of Prefabricated Buildings (Green Buildings) in Hainan Province (2023–2025)”, which clearly proposes to build good houses that are suitable for Hainan’s tropical climate and marine island characteristics [32]. It continuously carries out research on key technologies related to assembly-style buildings, green buildings, ultra-low (near zero) energy consumption buildings, low-carbon (zero-carbon) buildings, and other tropical building sciences under Hainan’s tropical marine island environmental conditions. Therefore, this article is based on the tropical island climate environment, rationally plans the comfortable and healthy energy demand of tropical island architecture, actively adopts structural optimization design using enclosure structure materials to promote energy conservation and carbon reduction, focuses on utilizing Hainan’s abundant renewable energy sources such as solar heat to support the building’s energy production capacity, and combines machine learning and multi-objective optimization algorithms to enable continuous optimization during the operation phase of tropical island architecture.

2.3. Tropical Island Zero-Carbon Buildings

According to the national dual carbon strategy and the requirements of Hainan’s clean energy free trade island construction, it is still necessary to vigorously promote energy conservation and carbon reduction in the construction industry for a considerable period until reaching the peak carbon dioxide emissions by 2060. ZCBs, which have zero carbon emissions during their operation, are considered as the key focus for achieving the dual carbon goals in the construction industry. By combining the concepts of ZCBs and tropical island buildings, this article defines TIZCB as follows: adapting to the climatic environmental characteristics of tropical islands, reflecting the regional culture of Hainan’s architecture, and on the basis of maintaining indoor healthy and comfortable environment energy demand, achieving building energy conservation through optimizing the design of enclosure structure systems, making full use of renewable energy for building body production capacity, and adopting integrated building design and intelligent control methods to make TIZCB technically feasible and economically reasonable. Among them, energy consumption is the foundation for creating a comfortable building environment; energy conservation is the prerequisite for new building energy-conservation design, and ZCBs are first and foremost green, low-carbon, and energy-conservation buildings; production capacity is the key to achieving ZCBs; and intelligence is the means of using intelligent methods for parameterized multi-objective regulation in integrated design, improving the efficiency of energy equipment and systems.

2.4. TIZCB Technology System

A TIZCB is a new technology system. In the past, for new building systems, emphasis was placed on technological research and innovation, while existing technology integration and innovation were neglected. This approach failed to balance the principles of technological advancement, feasibility, and reasonable economic costs, hindering the sustainable development of ZCBs. Analysis of ZCBs on tropical islands shows that they emphasize energy-conservation and production capacity technology system integration, as well as the prominent role of intelligent means in energy-conservation and carbon reduction during the design phase. Therefore, under the premise that there is no uniform definition standard for ZCBs at home and abroad, how to learn from foreign beneficial experiences, integrate key technologies such as environmental control energy-conservation and carbon reduction, passive energy-conservation and carbon reduction, skin production capacity carbon reduction, and system intelligence carbon reduction through quantitative evaluation and design optimization during the design phase, so that the implementation plan of ZCBs is technologically advanced and feasible, economically cost-effective, and thus establish a

ZCB technology system suitable for the climatic environment characteristics and economic development features of tropical islands, has become the key to the sustainable development of TIZCB. On the basis of meeting the technical indicators of ZCBs, by adopting low-carbon building materials, low-carbon structural forms, and material reduction design, it is possible to achieve total carbon emissions of not more than zero during the building operation process. The TIZCB technology system is shown in Table 1.

Table 1. TIZCB technology system.

Number	Classification	Main Technologies
1	Energy Utilization Technology	Ground (water) source heat pump system, displacement ventilation system, radiant cooling system, room personnel density and occupancy rate, electrical equipment power density and utilization rate, lighting schedule, etc.
2	Energy Conservation Technology	Exterior Wall Energy-Conservation Technologies: Wall composite technologies include an internal insulation layer, an external insulation layer, and a sandwich insulation layer. Door and Window Energy-Conservation Technologies: Double-glazed windows, multi-layer glass, coated glass (including reflective glass, absorbent glass), high-strength LOW2E fire-resistant glass (high-strength low-emissivity coated fire-resistant glass), and glass with a metallized silver layer. The airtightness of the building envelope. Roof Energy-Conservation Technologies: Solar heat collecting roofs and controllable ventilation roofs, etc.
3	Energy Production Technology	Development and Utilization of New Energy: Solar water heaters, photovoltaic roof panels, photovoltaic exterior wall panels, photovoltaic sun-shading panels, photovoltaic window walls, photovoltaic skylights, photovoltaic glass curtain walls, etc.
4	Intelligent Technology	Machine Learning Prediction Technology: AdaBoost Regressor, Bagging Regressor, CAT Boost Regressor, Decision Tree Regressor, Extra Tree Regressor, GBDT Regressor, KNeighbors Regressor, Lasso Regressor, LGBM Regressor, Linear Regressor, LSTM Regressor, Multilayer Perceptron Regressor, Random Forest Regressor, Support Vector Machine Regressor, XGBoost Regressor, etc. Intelligent Algorithm Optimization Technology: GA, NSGA-II, NSGA-III, etc. Techno-economic evaluation: Cost-benefit analysis, cost-effectiveness analysis, return on investment, net present value, internal rate of return, sensitivity analysis, risk analysis, life cycle cost analysis, multi-criteria decision analysis, etc.

3. Theoretical Methodology

3.1. System Theory

A system is an organic whole composed of several interacting, interdependent, and interconnected components that have specific functions. The system itself is also a part of a larger system to which it belongs. System theory aims to explore and understand the nature, structure, and behavior of systems, emphasizing the use of holistic thinking to investigate the laws of things and using mathematical models to define, express, and quantify the characteristics and functions of systems.

In the early 20th century, Ludwig von Bertalanffy, an Austrian biologist of American nationality, was the founder of General Systems Theory (GST, 1968) [33]. He defined a system as “a complex composed of several interacting elements”, thus defining the three basic characteristics of purposefulness, dynamics, and orderliness of systems theory and emphasizing the importance of system thinking [34]. Bertalanffy’s work inspired other scholars, including Bertalanffy’s work inspired other scholars, including Talcott Parsons and Niklas Luhmann, who applied systems theory to the study of social systems [35]. In the mid-20th century, ecologists Howard T. Odum and Eugene P. Odum introduced system theory into the field of ecology, pioneering research in ecosystem ecology, energy ecology, etc., and proposing the ecosystem theory [36]. Fritjof Capra combined systems theory with ecology, physics, and philosophy at the end of the 20th century, proposing the connection between ecology and science [37]. Peter Senge, on the other hand, proposed a theory of organizational learning in the fields of organizational science and management,

applying system thinking to organizational management [38]. Modern systems science has promoted interdisciplinary research and the spread of systemic thinking in various fields, while also facilitating interdisciplinary collaboration among different domains, including engineering, ecology, sociology, management, and environmental science [39]. This helps in understanding and addressing complex issues [40].

Overall, systems theory underscores the interdependent, interactive, and constraining relationships between the whole and parts, among parts, and between the system itself and its external environment. This facilitates the analysis of complex system behaviors, optimization of system performance, and support for decision-making. Regarding the technological system of ZCB systems theory allows for the building to be viewed at a macro-level as an entity comprising distinct systems with different functional characteristics. This approach involves two fundamental steps: system deconstruction and system integration. System deconstruction entails dividing the building into various technical systems based on different target functions, each characterized by distinct functionalities. System integration then combines these technical systems into a building system that is highly cohesive and loosely coupled.

3.2. Cybernetics

The basic idea of cybernetics is to achieve effective control and management of a system by understanding the interactions between its various components. Its core concept is circular causality or feedback, where the result of an action serves as input for further actions. Cybernetics studies the state, function, behavior, and changing trends of systems, revealing common control laws for different systems through stable control of systems.

Control theory originated in the 1940s, with early contributors including Norbert Wiener, Warren McCulloch, Arturo Rosenblueth, etc. They promoted the formation of control theory at events such as Macy Conferences. Control theory broke free from the constraints of Newtonian classical mechanics and Laplacian mechanical determinism, using new statistical theories to study various possibilities for system motion states, behavior patterns, and changing trends [41]. The work of scholars like Jay Wright Forrester in the field of system dynamics has provided significant support for the development of cybernetics [42]. The concept of intelligent control emerged in the 1960s. With the increasing uncertainty, high dimensionality, and nonlinearity of things [43], new methods and technologies such as uncertain mathematical models and high-dimensional nonlinear intelligent means have gradually gained prominence [44]. In the 1970s, new cybernetic researchers such as Humberto Maturana proposed a new cybernetics that is more adaptable to biological systems [45], guiding the evolution of the field. The application of economists like Oskar Ryszard Lange in economic systems also provides a new perspective for the expansion of cybernetics [46]. Control theory has a wide range of concerns [47], including environmental, technological, biological, cognitive, and social systems [48], as well as practical activities such as design, learning, management, and dialogue [49].

Overall, cybernetics provides a systematic approach to thinking and methodology that aids in understanding and optimizing the comprehensive performance of building systems. It allows for perception, learning, and adjustment at the micro-level, quantifying the parametric design model of TIZCB systems. This forms the basis for the intelligent control of building systems, aiming to achieve multi-objective optimization of various systems, thereby promoting innovation and optimization in architectural design. This involves two fundamental steps: system quantification and system control. System quantification involves characterizing and modeling the system parameters obtained from system deconstruction to reveal the quantitative laws of each system. System control, based on understanding the operational laws of each system, adjusts the quantified parameters within the system to achieve the optimization of system objectives.

3.3. Synergetics

Synergetics is a discipline that studies the interaction and synergistic effects of systems. Synergy refers to the collective effect produced by the interaction of subsystems in complex systems. Synergetics believes that things are unified entities organized by many systems, with complementary, collaborative, and coordinated relationships between subsystems. It points out that the coupled evolution of natural systems and social systems from disorder to order is the result of mutual influence, interaction, and constraint among the elements of the system.

Synergetics, proposed by West German scientist Hermann Haken in the 1970s, emphasizes the generation of ordered structures and the issue of maintaining a constant supply of energy within a system. It further addresses the challenge of how complex systems transition from a state of disorder to order, facilitating the self-organizing evolution of systems from disorder to order. This transformation allows for the realization of system efficiency where $1 + 1$ becomes greater than 2, transcending the conventional understanding of $1 + 1 \leq 2$ [50]. After decades of integrated development, modern synergetics has evolved from the “old trinity” of system theory, information theory, and dissipative structure theory within general systems theory to the “new trinity” of self-organizing system analysis. This progression has significantly advanced the theoretical foundations of self-organizing systems. Architects and structural engineers, such as Richard Buckminster Fuller and Marshall Applewhite, noted in “Synergetics: Explorations in the Geometry of Thinking” that synergetics reveals the logical principles governing natural laws, and they applied synergetic concepts in the field of architecture. The theoretical framework of synergetics combines system dynamics with statistics, providing essential conceptual tools for the study of the dynamic evolution of complex systems from micro- to macro-levels [51]. This integration has accelerated the development of modern nonlinear science and systems theory, highlighting synergetics as an intrinsic and essential force driving the internal evolution and formation of new ordered structures within systems [52]. Synergetics has laid the foundation for the study of ordered structures within various interdisciplinary fields. It finds extensive application in the control processes of engineering and technological systems [53], socio-economic systems [54], and ecological and environmental systems, among other domains [55].

Overall, systems theory emphasizes the interactive relationships of mutual action, influence, and constraint among systems, highlighting how coordinated coupling can generate new system structures, offering an important cognitive tool for studying complex system patterns. For the TIZCB systems, synergy theory explores the internal laws of several building systems from both qualitative and quantitative perspectives at the meso-level. This process involves two basic steps: system interaction and system coupling. System interaction involves comparative analysis and preparatory integration of concepts and definitions among systems, representing a qualitative level of system study; system coupling involves quantitative analysis and integrated optimization of models and relationships following system interaction, representing a quantitative level of system exploration.

3.4. Overview of Theoretical Application

The method system and technical approach of system theory, synergy theory, and control theory provide a new perspective for the deconstruction, integration, coupling, interaction, and intelligent control of the enclosure structure system in TIZCB, as illustrated in Figure 1.

Analyzing Figure 1, the interrelationship among these three methods is as follows: (1) systems theory divides and integrates TIZCB into four systems; (2) synergetics facilitates the interactive coupling of the four systems in TIZCB, which is crucial for technological updates and cost reduction in TIZCB; and (3) cybernetics, through “Intelligent Technology”, implements “Energy Utilization Technology”, “Energy Conservation Technology”, and “Energy Production Technology” in TIZCB. Lastly, supporting the rest of the study with these three theoretical methods indeed provides a solid theoretical foundation and

practical significance, especially in offering significant guidance for the rational division of building systems.

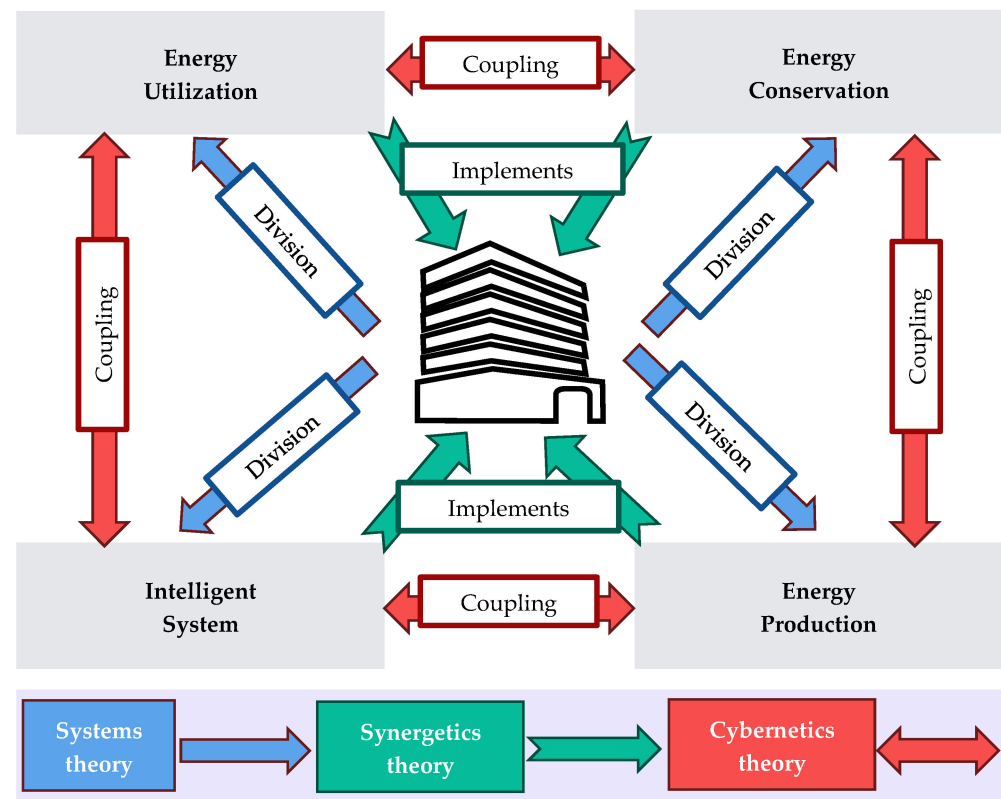


Figure 1. Overview of theoretical application.

4. Establishing a Theoretical Framework

4.1. Macroscopic System Decomposition and Integration

System theory, operating at the macro-level, conducts goal decomposition and system integration for the technical system of ZCBs. Its objective is to approach the energy conversion aspects such as energy utilization, conservation, and production, focusing on energy-efficient comfort and the goals of new industrialization in building construction. System theory perceives TIZCB as complex systems and systematically organizes the energy utilization, conservation, production, and intelligent technology systems in these buildings. This is achieved through defining functional objectives, analyzing complex systems, optimizing system feedback, and ultimately forming the macro-system decomposition and integration of TIZCB, as illustrated in Figure 2.

Analyzing Figure 2, it is evident that the key to the decomposition and integration of the macro-level technical system lies in goal identification and system integration. In accordance with tropical island building regulations, climate characteristics, and constituent elements, applicable technical systems for TIZCB are systematically outlined. Focusing on the requirements of zero-carbon construction, energy-efficient comfort, and the goals of new industrialization, the technical system for TIZCB is defined from the perspectives of building energy flow and intelligent control. The identified four major goals for the technical system of TIZCB are “precise energy utilization and carbon reduction at the environmental control endpoints, passive energy conservation in the building envelope, efficient energy production in the building shell, and intelligent coupling and control for carbon reduction”. These goals are integrated into the four major systems of the technical system for TIZCB, namely, the energy utilization system, energy conservation system, energy production system, and intelligent system. Specifically, the energy utilization system describes the basic energy consumption in creating a comfortable building environment,

focusing on the energy planning of the building's environmental control system. The energy conservation system characterizes the integrated optimization design through the building envelope, focusing on energy-conservation components such as walls, doors, windows, and roofs. The energy production system depicts the utilization of renewable energy technologies, particularly photovoltaic and solar-thermal integration, focusing on the integrated energy-producing surface of walls, doors, windows, and roofs. The intelligent system represents the use of intelligent methods for integrated design with parameterized multi-objective control, achieving technically advanced and economically reasonable integrated designs for energy planning, energy-conservation components, and energy-producing surfaces.

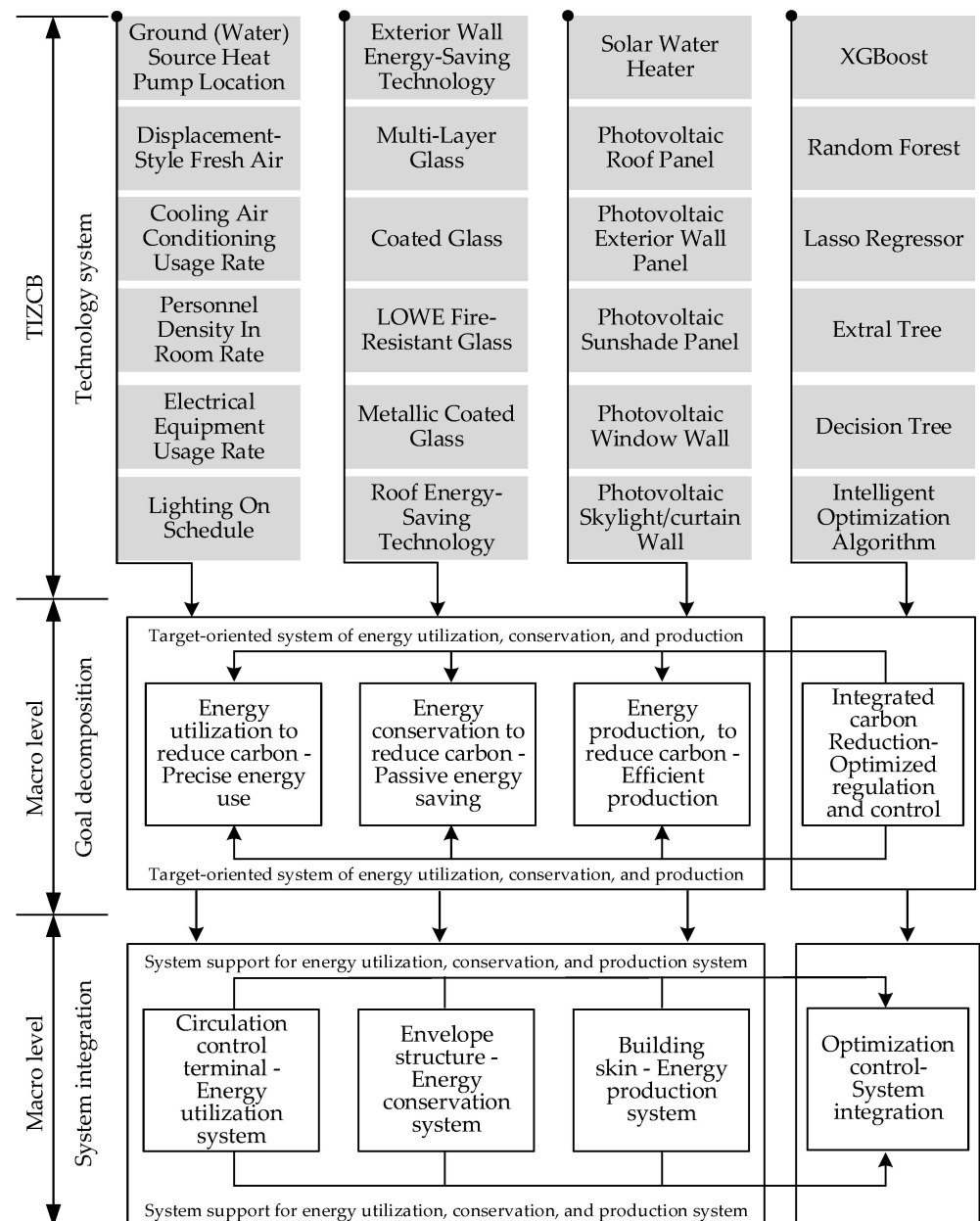


Figure 2. Macro system decomposition and integration of TIZCB based on system theory.

Overall, decomposition and integration involve defining functional modules, analyzing complex systems, and optimizing system feedback to achieve energy-conservation and green comfort in buildings. Through the analytical process of decomposition and integration based on system theory, the technical system of TIZCB is viewed as a complex

system. The functional goals of the TIZCB technical system are decomposed, and the four major systems of “energy utilization, energy conservation, energy production, and intelligent systems” are integrated. Therefore, it is crucial to recognize that while macro-level decomposition and integration of the four systems of energy utilization, conservation, production, and intelligent systems are essential, a micro-level understanding of the internal influencing mechanisms of these systems is equally important. This micro-level analysis forms the basis for exploring the mechanisms of TIZCB systems and is critical for achieving the goals of energy-conservation comfort and new industrialization in TIZCB.

4.2. Microparameter Quantification and Regulation

Control theory, operating at the micro-level, involves quantifying and intelligently controlling design parameters for ZCBs. This process constitutes the micro-level quantification and regulation of parameters in TIZCB, as illustrated in Figure 3.

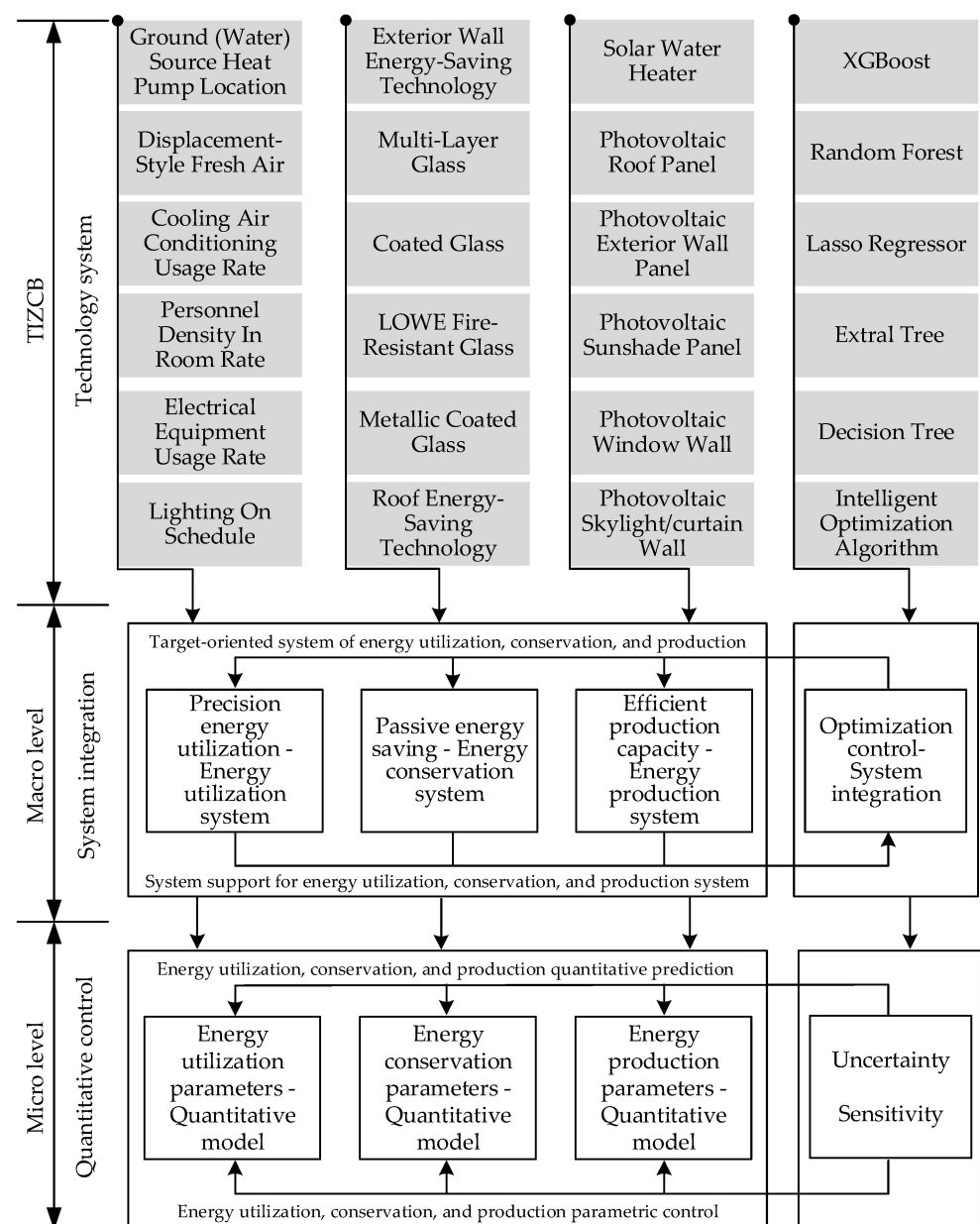


Figure 3. Microscopic parameter quantification and regulation of TIZCB based on cybernetics.

From the analysis of Figure 3, it is evident that the key to micro-level quantification and regulation lies in quantitative prediction and intelligent control. Its objective is to quantitatively predict and intelligently control the design parameters of the energy utilization, conservation, and production systems in TIZCB. Using machine learning models from intelligent systems, the theory aims to reveal the impact mechanisms of variations in design parameter combinations on building performance through quantitative simulation results. Intelligent control of the energy utilization, conservation, and production systems is achieved through multi-objective optimization algorithms. Based on the functional goals of the energy utilization, conservation, and production intelligent system in TIZCB, a model for quantifying design parameters of the energy utilization, conservation, and production systems is constructed. Intelligent systems incorporating machine learning and optimization algorithms are developed. Building upon this foundation, through quantitative simulation, performance prediction, and multi-objective optimization, the study reveals the impact mechanisms of variations in design parameter combinations on building performance. It explores the optimal combinations of design parameters for the energy utilization, conservation, and production systems in TIZCB at the micro-level. The micro-level quantification and regulation of design parameters determine the direction of modular, parameterized, and intelligent optimization design for the energy utilization, conservation, and production systems in TIZCB. This establishes the basic premise for studying the mechanism of energy utilization, conservation, and production intelligent systems and provides specific implementation plans. Quantitative prediction focuses on predictive analysis of the energy utilization, conservation, and production systems in TIZCB using machine learning integrated models built by intelligent systems. Intelligent control, based on predictive analysis, utilizes multi-objective intelligent optimization algorithms to optimize the energy utilization, conservation, and production systems, achieving optimal performance in the integrated design of energy planning, conservation components, and production surfaces in TIZCB. Overall, quantification and regulation constitute the process of revealing system regularities, exploring system mechanisms, and achieving optimal design parameter combinations for building performance. The process of quantification and regulation based on control theory proposes a conceptual framework for quantifying design parameters of the energy utilization, conservation, and production systems in TIZCB and constructs an intelligent system prediction optimization method based on data-driven approaches. Therefore, it is essential to recognize that, while decomposing and integrating the four major systems at the macro-level and quantifying and regulating the impact mechanisms at the micro-level, achieving the interaction and coupling of building systems and design parameters at the meso-level is crucial. This is a prerequisite for the integration of energy planning, conservation components, and production surface technologies and a key factor in realizing the integrated design of TIZCB.

4.3. Interaction and Coupling of Mesoscopic Systems

Synergetics, operating at the mid-level, engages in model interaction and goal coupling of TIZCB systems. Its aim is to, on the basis of model interaction in the energy utilization, conservation, and production systems of TIZCB, employ intelligent systems for multi-system quantified prediction and multi-objective control decision-making of the coupled systems. This process utilizes the mid-level building system interaction and coupling to link the macro-level technical systems and micro-level design parameters. Figure 4 illustrates the interaction and coupling of the mid-level system in TIZCB. The mid-level interaction coupling generates a multi-system coupled quantification model, laying the foundation for achieving the overall performance optimization goals of energy utilization planning, energy-conservation components, and capacity-building skin at the macro-level. This illustrates that mid-level interaction fusion of energy utilization, conservation, and production systems has become a crucial link in connecting the macro and micro-levels.

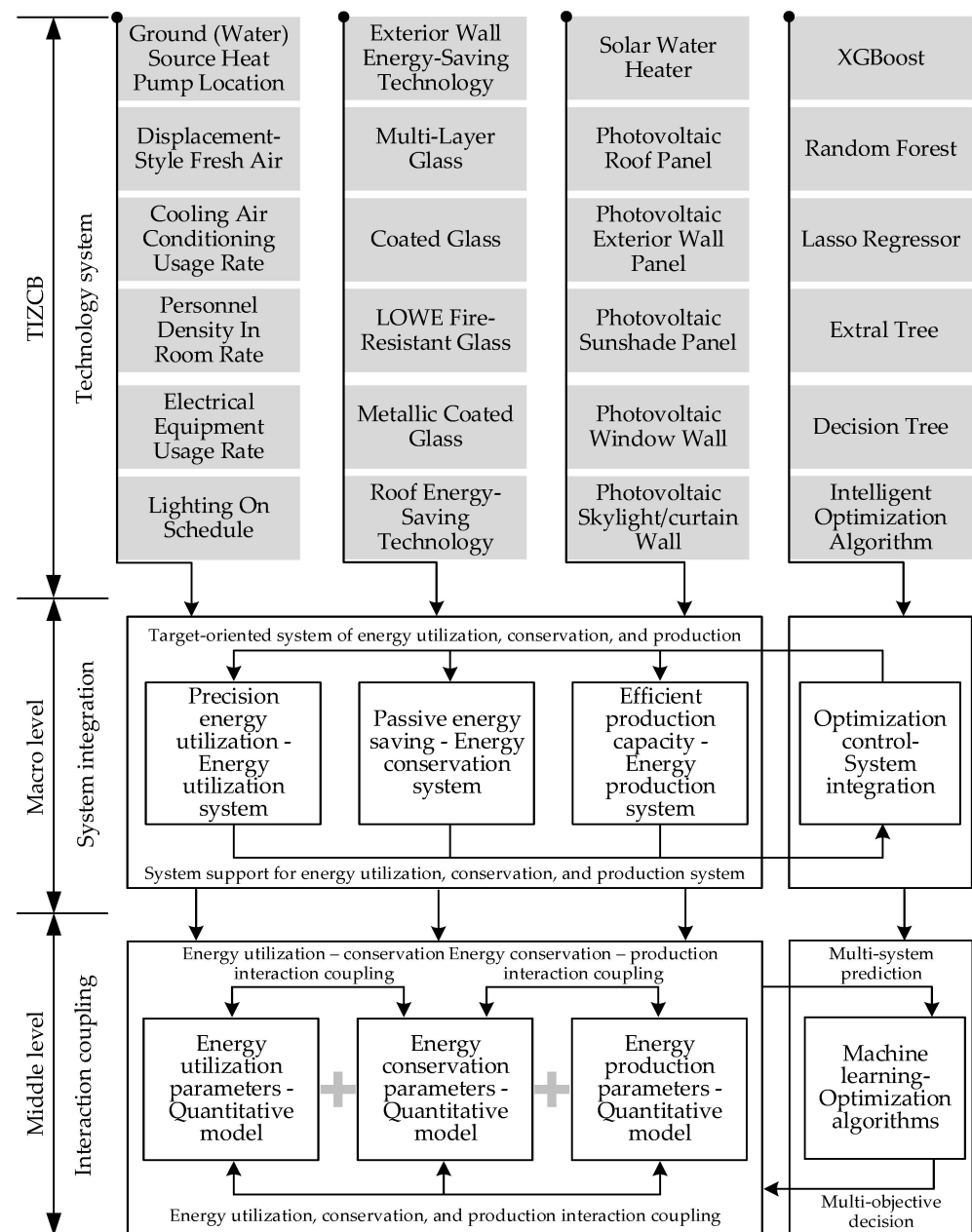


Figure 4. Intermediate interaction and coupling in TIZCB systems based on synergistics.

Analyzing Figure 4, it is evident that the key to mid-level interaction and coupling lies in multi-system quantified prediction and multi-objective control decisions. Building upon the macro-level decomposition of the four major goals, namely “precise energy reduction in environmental control, passive energy reduction in envelope structure, efficient energy reduction in building skin, and intelligent reduction in carbon through integrated control of systems” and the integration of the four major systems, namely “energy utilization system, energy-conservation system, capacity-building system, and intelligent system”, intelligent systems with integrated learning models and optimization algorithms are utilized. This is carried out for the quantified prediction and intelligent control of design parameters at the micro-level of the energy utilization, conservation, and production system. Further, the coupled systems of energy utilization, conservation, and production undergo multi-system quantified prediction and multi-objective control decisions, thereby achieving the organic unity of the technical system, building system, and design parameters in the intelligent

system of TIZCB. The macro-level derivation and integration of the four major systems provide a fundamental guideline for micro-level quantification and control.

Overall, interaction and coupling involve the interplay of system models and the coupling of system goals, realizing the optimization of design parameter combinations for the overall performance of TIZCB. Based on the analysis of the interaction and coupling process using synergetics and building on research at the macro- and micro-levels, a research path is proposed for the quantified prediction of multi-systems and the multi-objective control decision-making of energy utilization, conservation, and production in TIZCB. This forms the basis for the evaluation of intelligent system technology and economic analysis in TIZCB. It is crucial to recognize that the overall performance of TIZCB is not simply the sum of energy utilization, conservation, production, and intelligent systems. Instead, it is the result of the mutual influence, interaction, and constraint of each system. By exploring the optimal levels of each system, understanding the coupling effects and principles of each system's complex relationships, the overall energy and carbon reduction in TIZCB can be effectively optimized.

4.4. Analysis of Intelligent Systems Based on Macro–Medium–Micro

To theoretically explore the mechanisms of energy utilization, conservation, production, and intelligent systems in TIZCB and to summarize the research focus while elucidating the research approach, this section employs system engineering theories such as system theory, synergetics, and control theory. The analysis is conducted through processes that involve macro-level goal decomposition and system integration, micro-level model quantification and parameter control, and meso-level parameter interaction and system coupling. The resulting framework, as illustrated in Figure 5, establishes a comprehensive analysis structure for understanding the mechanisms of energy utilization, conservation, production, and intelligent systems in TIZCB based on macro–meso–micro perspectives.

From the analysis of Figure 5, a horizontal perspective reveals the following: At the macro-level, the four major goals of “precision energy utilization reduction, passive energy conservation of enclosure structure, efficient energy production of building envelope, and intelligent regulation for integrated control to reduce carbon emissions” are decomposed. This results in the integration of the TIZCB technical system into four major systems: “energy utilization system, energy conservation system, production system, and intelligent system”. At the micro-level, a quantitative model of design parameters for the “energy utilization system, energy conservation system, and production system” is established. Machine learning and optimization algorithms from the “intelligent system” are then applied to quantitatively predict and intelligently control the three major quantitative models of energy utilization, conservation, and production systems. At the meso-level, interactions occur among the “energy utilization system, energy conservation system, and production system”, and coupling takes place among the “energy parameter, conservation parameter, and production parameter” quantitative models. This achieves system quantification prediction and multi-objective intelligent control of the coupled model of energy utilization, conservation, and production through the “intelligent system” for technical evaluation and economic analysis. From a vertical perspective, building upon the analysis of technical system goals and system integration at the macro-level, the micro-level design parameter quantification prediction and intelligent control are carried out. This achieves a direct mapping from the macro to the micro-level, laying the foundation for the micro-level quantification of macro goals. At the meso-level, using system interaction and goal coupling as intermediaries, macro-level technical systems and micro-level design parameters are interactively coupled and organically linked. This results in multi-system quantification prediction and multi-objective intelligent control of energy utilization, conservation, and production. Thus, the framework for analyzing TIZCB systems is established at multiple levels, including macro, meso, and micro, encompassing multiple systems, and addressing multiple objectives in terms of technical evaluation and economic analysis.

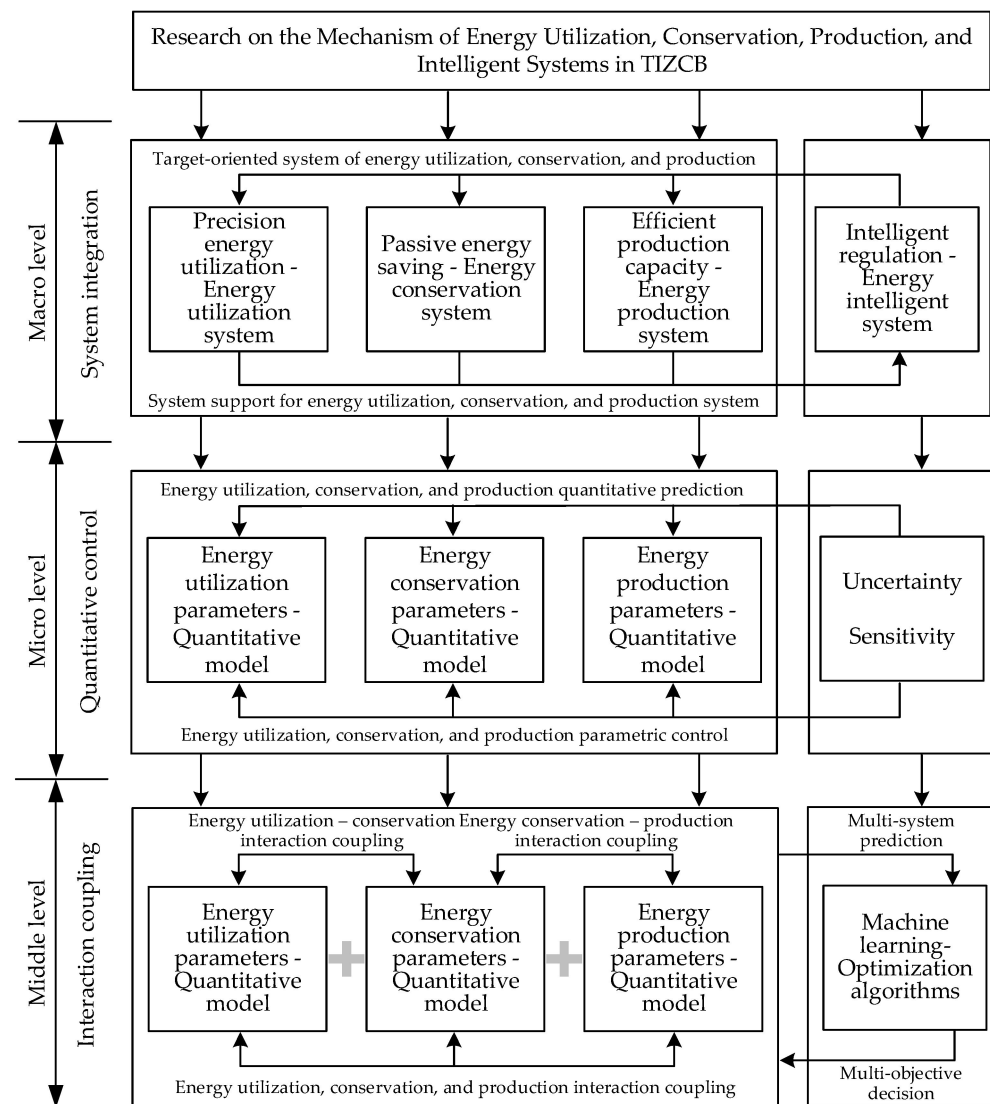


Figure 5. Analysis framework of TIZCB systems based on macro–meso–micro perspectives.

Overall, the TIZCB system analysis framework based on macro–meso–micro perspectives aims to provide a holistic, multi-level, multi-system, and multi-objective research perspective from global to local and macro to micro. This framework assists in exploring and understanding the parameterized model construction, influencing relationships, and optimization analysis of energy utilization, conservation, production, and intelligent systems in TIZCB from various perspectives. It establishes a theoretical foundation for the study of mechanisms in the energy utilization, conservation, production, and intelligent systems of TIZCB.

5. Research Logical Framework

To support China’s dual-carbon strategy in the construction industry and the establishment of Hainan as a clean energy free trade island, this study addresses the current challenges in TIZCB standards, including inconsistent definitions, incomplete technical systems, and immature integrated applications. Focusing on the demands for energy conservation, comfort, and the new industrialization of buildings and considering the unique climate characteristics of Hainan’s tropical island environment, this paper explores the energy utilization, conservation, production, and intelligent systems in TIZCB. It employs methods from systems engineering and parametric design technology to summarize and address common issues such as “how to accurately establish quantitative models for system

design parameters and building performance”, “how to finely investigate the relationships between system design parameters and building performance”, and “how to dynamically optimize system design parameters and building performance for comprehensive objectives”. The study systematically distills the key scientific and technological problem of “mechanisms and intelligent optimization methods for the energy utilization, conservation, production, and intelligent systems in TIZCB”. The framework for theoretical analysis and research entitled “Mechanisms of the Energy Utilization, Conservation, Production, and Intelligent System in TIZCB” is established as a crucial component. Corresponding research contents include “Mechanism of the Energy Utilization System in TIZCB”, “Mechanism of the Energy Conservation System in TIZCB”, “Mechanism of the Production System in TIZCB”, and “Mechanism of the Intelligent System in TIZCB”. These components collectively contribute to the objectives of “establishing a quantitative model for the design parameters of the energy utilization, conservation, production, and intelligent system in TIZCB”, “achieving a quantitative analysis of the energy utilization, conservation, production, and intelligent system in TIZCB”, and “optimizing the comprehensive objectives of the energy utilization, conservation, production, and intelligent system in TIZCB”. The overall research framework for the energy utilization, conservation, production, and intelligent system in TIZCB is illustrated in Figure 6.

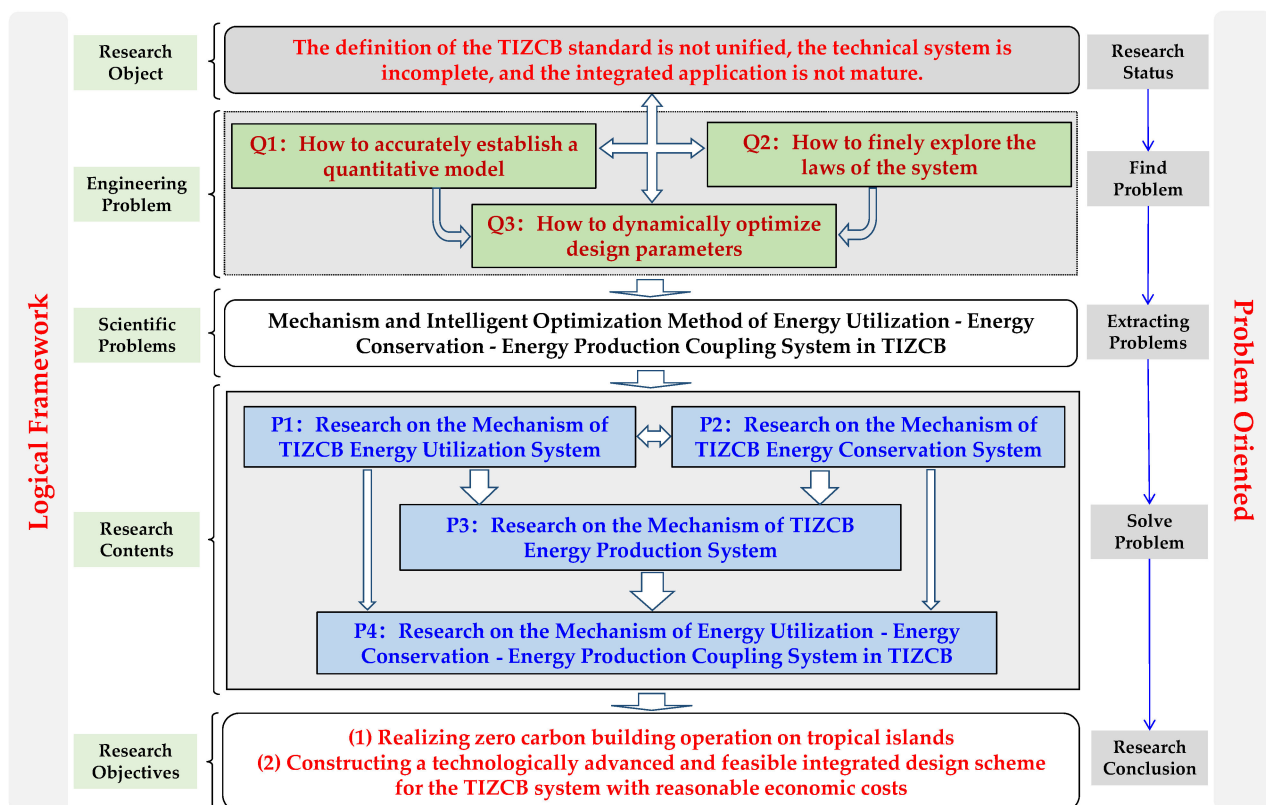


Figure 6. Comprehensive research approach for TIZCB.

6. Research Implementation Plan

6.1. TIZCB Energy Utilization System Mechanism Research Plan

6.1.1. Research Objectives

To survey and analyze the distribution characteristics of energy utilization parameters in tropical island buildings and establish a parametric design reference model based on the goals of TIZCB. Through quantitative simulation and sensitivity analysis of the energy utilization system, reveal the impact relationships between variations in design parameter combinations of the TIZCB energy utilization system islands and building performance. Develop data-driven models for building performance prediction and multi-objective

optimization analysis, forming optimized combinations of design parameters for the energy utilization system in TIZCB.

6.1.2. Main Contents

(1) Construction of a Parametric Model for the Energy Utilization System in TIZCB

First, based on tropical island building design standards and climate characteristics, conduct research on design parameters such as personnel, equipment, HVAC systems, lighting control, and ventilation strategies in the energy utilization system of TIZCB. Then, utilize statistical analysis software to process research data, perform reliability and validity tests, and employ methods such as descriptive statistics, correlation analysis, and regression analysis to reveal the distribution patterns of design parameters in the TIZCB energy utilization system. Finally, based on the characteristics of energy utilization parameter distribution, select typical design parameters for the energy utilization system and, with reference to tropical island building design standards, establish a parametric design reference model based on the goals of TIZCB.

(2) Impact Relationships between the Design Parameters of the Energy Utilization System and Building Performance in TIZCB

First, based on the distribution characteristics of energy utilization system design parameters, use the Latin hypercube sampling (LHS) method to sample design parameters for the energy utilization system in TIZCB. Generate parameterized design schemes suitable for the batch input of IDF scripts in EnergyPlus and simulate the energy utilization system in batches using the Jeplus plugin. Then, using quantitative tools such as histograms, scatter plots, and standard regression coefficients, conduct correlation, determinacy, and uncertainty analyses of energy utilization system design parameters. Finally, perform local and global sensitivity analyses of energy utilization system design parameters based on the R language, revealing the impact relationships between variations in design parameter combinations of the TIZCB energy utilization system and building performance.

(3) Optimization Analysis of the Impact of the Design Parameters of the Energy Utilization System on Building Performance in TIZCB

First, based on the characteristics of energy utilization parameters and building performance indicators, select machine learning prediction models such as Bayesian regression, ridge regression, linear regression, support vector machine regression, random forest regression, and artificial neural networks. Construct a data-driven prediction and analysis model for the TIZCB energy utilization system. Then, use metrics such as RMSE, MSE, SE, MAPE, MAE, and NMSE to evaluate the model. Build multiple integrated models with excellent performance and conduct predictive analyses of energy utilization parameters and building performance. Finally, based on the predictive analysis, conduct multi-objective analyses of building performance indicators using intelligent optimization algorithms, forming optimized combinations of design parameters for the energy utilization system in TIZCB.

6.2. TIZCB Energy Conservation System Mechanism Research Plan

6.2.1. Research Objectives

To survey and analyze the thermal parameters of building energy conservation systems on tropical islands, establish a parametric design reference model based on the goals of TIZCB. Through quantitative simulation and sensitivity analysis of the thermal parameters of the energy conservation system, reveal the impact relationships between variations in design parameter combinations of the TIZCB energy conservation system and building performance. Under the guidance of thermal parameters, establish a material-structure parametric design model, develop data-driven models for building performance prediction, and form optimized combinations of design parameters for the energy conservation system in TIZCB.

6.2.2. Main Contents

(1) Construction of a Parametric Model for the Energy Conservation System in TIZCB

First, based on building design standards, climate characteristics, and energy utilization habits on tropical islands, research thermal performance parameters such as window-wall ratio, solar heat gain coefficient, and heat transfer coefficient. Then, use statistical analysis software to process research data, perform reliability and validity tests, and employ methods such as descriptive statistics, correlation analysis, and regression analysis to reveal the distribution patterns of thermal performance design parameters in the energy conservation system. Finally, based on the characteristics of thermal parameter distribution, select typical design parameters for the energy conservation system and, with reference to tropical island building design standards, establish a parametric design reference model based on the goals of TIZCB.

(2) Impact Relationships between Design Parameters of the Energy Conservation System and Building Performance in TIZCB

First, based on the distribution characteristics of thermal parameters in the energy conservation system, use the Latin hypercube sampling (LHS) method for sampling. Generate parameterized design schemes suitable for the batch input of IDF scripts in EnergyPlus and simulate the thermal parameters of the energy conservation system in batches using the Jeplus plugin. Then, using quantitative tools such as histograms, scatter plots, and standard regression coefficients, conduct correlation, determinacy, and uncertainty analyses of thermal design parameters in the energy conservation system. Finally, perform local and global sensitivity analyses of thermal design parameters based on the R language, revealing the impact relationships between variations in design parameter combinations of the TIZCB energy conservation system and building performance.

(3) Optimization Analysis of the Impact of the Design Parameters of the Energy Conservation System on Building Performance in TIZCB

First, under the guidance of thermal parameters, conduct batch simulations of material performance (thermal conductivity, density, and specific heat) and structural system (wall orientation, construction hierarchy, and material thickness) combination design parameters. Then, select machine learning prediction models such as Bayesian regression, ridge regression, linear regression, support vector machine regression, and random forest regression. Construct a data-driven prediction and analysis model for the TIZCB energy conservation system. Use metrics such as RMSE, MSE, SE, MAPE, MAE, and NMSE to evaluate the model. Build multiple integrated models with excellent performance and conduct predictive analyses of thermal parameters and building performance. Finally, based on the predictive analysis, conduct multi-objective analyses of building performance indicators using intelligent optimization algorithms, forming optimized combinations of design parameters for the energy conservation system in TIZCB.

6.3. TIZCB Production System Mechanism Research Plan

6.3.1. Research Objectives

To survey and analyze the distribution characteristics of building production parameters on tropical islands, establish a parametric design reference model based on the goals of TIZCB. Through quantitative simulation and sensitivity analysis of the production system, reveal the impact relationships between variations in design parameter combinations of the TIZCB production system and building performance. Develop data-driven models for building performance prediction, and form optimized combinations of design parameters for the production system in TIZCB.

6.3.2. Main Contents

(1) Construction of a Parametric Model for the Production System in TIZCB

First, based on building design standards, climate characteristics, and energy utilization habits on tropical islands, research design parameters such as photovoltaic–thermal integrated walls, multifunctional photovoltaic windows, and photovoltaic–thermal integrated roofs. Then, use statistical analysis software to process research data, perform reliability and validity tests, and employ methods such as descriptive statistics, correlation analysis, and regression analysis to reveal the distribution patterns of design parameters in the production system. Finally, based on the characteristics of production parameter distribution, select typical design parameters for the production system and, with reference to tropical island building design standards, establish a parametric design reference model based on the goals of TIZCB.

(2) Impact Relationships between the Design Parameters of the Production System and Building Performance in TIZCB

First, based on the distribution characteristics of design parameters in the production system, use the Latin hypercube sampling (LHS) method for sampling. Generate parameterized design schemes suitable for the batch input of IDF scripts in EnergyPlus and simulate the production system in batches using the Jeplus plugin. Then, using quantitative tools such as histograms, scatter plots, and standard regression coefficients, conduct correlation, determinacy, and uncertainty analyses of design parameters in the production system. Finally, perform local and global sensitivity analyses of design parameters based on the R language, revealing the impact relationships between variations in design parameter combinations of the TIZCB production system and building performance.

(3) Optimization Analysis of the Impact of the Design Parameters of the Production System on Building Performance in TIZCB

First, based on the characteristics of production parameters and building performance indicators, select machine learning prediction models such as Bayesian regression, ridge regression, linear regression, support vector machine regression, random forest regression, and artificial neural networks. Construct a data-driven prediction and analysis model for the TIZCB production system. Then, use metrics such as RMSE, MSE, SE, MAPE, MAE, and NMSE to evaluate the model. Build multiple integrated models with excellent performance and conduct predictive analyses of production parameters and building performance. Finally, based on the predictive analysis, conduct multi-objective analyses of building performance indicators using intelligent optimization algorithms, forming optimized combinations of design parameters for the production system in TIZCB.

6.4. TIZCB Intelligent System Mechanism Research Plan

6.4.1. Research Objectives

To interact and couple the design parameters of energy utilization, conservation, and production systems to obtain the distribution characteristics of the intelligent system and design parameters in TIZCB. Establish a parametric design reference model based on the goals of TIZCB. Develop data-driven models for building performance prediction and multi-objective optimization analysis, forming optimized combinations of design parameters for the intelligent system in TIZCB. Under the premise of achieving the zero-carbon operation goal of tropical island buildings, conduct an economic evaluation of the optimized combinations of design parameters for the intelligent system, obtaining economically reasonable design parameter combinations for the intelligent system in TIZCB.

6.4.2. Main Contents

(1) System-Coupled Parametric Modeling of the Intelligent System in TIZCB

First, interact the combined design schemes of the energy utilization, conservation, and production systems in TIZCB. Form the intelligent system of TIZCB through the coupling

of the energy utilization—conservation—production system. Then, outline the technical solutions for the energy utilization planning, conservation components, and production system integrated design technologies of the intelligent system. Obtain the distribution characteristics of the design parameters of the intelligent system in TIZCB. Finally, based on the distribution characteristics of intelligent system parameters, select typical design parameters for the intelligent system and, with reference to tropical island building design standards, establish a parametric design reference model based on the goals of TIZCB.

(2) Technical Evaluation-Based Optimization and Regulation of the Intelligent System in TIZCB

First, based on the distribution characteristics of intelligent system design parameters, use the Latin hypercube sampling (LHS) method to sample design parameters for the intelligent system in TIZCB. Generate parameterized design schemes suitable for the batch input of IDF scripts in EnergyPlus and simulate the intelligent system in batches using the Jeplus plugin. Then, based on the distribution characteristics of intelligent system parameters, select machine learning prediction models such as Bayesian regression, ridge regression, linear regression, support vector machine regression, random forest regression, and artificial neural networks. Construct a data-driven prediction and analysis model for the TIZCB intelligent system. Use metrics such as RMSE, MSE, SE, MAPE, MAE, and NMSE to evaluate the model. Build multiple integrated models with excellent performance and conduct predictive analyses of intelligent system parameters and building performance. Finally, based on the predictive analysis, conduct multi-objective analyses of building performance indicators using intelligent optimization algorithms, forming optimized combinations of design parameters for the intelligent system in TIZCB.

(3) Decision Assessment of the TIZCB Intelligent System Based on Economic Evaluation

Firstly, based on the optimization and control results of the intelligent system in TIZCB, analyze the numerical relationship between energy utilization, energy conservation, and production systems to obtain an integrated optimization scheme for achieving zero-carbon operation of the building. Subsequently, apply the life cycle cost analysis method to evaluate the initial investment, operational maintenance, energy conservation, and equipment replacement costs of the integrated optimization scheme. Establish an economic decision assessment model for the integrated optimization scheme. Finally, through sensitivity analysis, identify and quantify uncertainties in economic evaluations, and formulate a technically advanced, feasible, and economically reasonable integrated optimization scheme for the intelligent system design in TIZCB.

7. Conclusions

- (1) This study defines TIZCB, achieving ZCBs during building operation by relying entirely on renewable energy sources. It emphasizes the need for architectural design to adapt to tropical climate conditions, integrate local culture, and utilize innovative technologies and materials. A technical framework is proposed, focusing on energy utilization, energy conservation, energy production, and intelligent technologies, grounded in theories including system theory, control theory, and synergy theory.
- (2) Using a macro–meso–micro analytical framework for TIZCB, this study outlines the macro objectives and micro parameter controls of such systems. System theory is employed for goal setting, control theory for parameter prediction, and synergy theory for establishing system interactions, providing a foundation for practical design and optimization.
- (3) By integrating systems engineering theory and parametric design technology, this research investigates the impact of design parameter models on the performance of ZCBs. A theoretical framework is established covering energy utilization, energy conservation, energy production, and intelligent systems, offering clear research strategies for implementation.

- (4) Through meticulous planning, this study develops parameter models and data-driven analysis for TIZCB, ensuring both zero-carbon operation and economic feasibility. It provides a systematic framework and practical guidance to advance clean energy development in Hainan and China's dual-carbon strategy.
- (5) The TIZCB proposed in this study achieves zero carbon emissions only during the building operation phase. The next step is to advance TIZCB to further reduce carbon emissions from a whole lifecycle perspective; on the other hand, the framework and technical solutions proposed in this study still need to be validated in actual cases.

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