Research on Space Optimization and Building Performance Improvement in Prefabricated Residential Design

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Keywords: space optimization; building performance; prefabricated residential

Abstract: As an efficient and environmentally-friendly construction method, the space optimization and building performance improvement of prefabricated housing are the key factors affecting its popularization and application. This paper discusses the strategies of space optimization in the design of prefabricated houses, including modular and standardized design, variable and adaptive space design, composite function and integrated design, and refined size and ergonomic design. At the same time, the paper analyzes the methods to improve building performance through design optimization, material selection and system integration, including structural performance and safety improvement, energy saving and environmental protection performance improvement, indoor environment quality improvement, intelligent operation and maintenance and long-term performance improvement. Finally, through empirical research, this paper compares and analyzes the performance improvement in space efficiency, energy-saving effect and indoor environment between the assembled residence with optimized design scheme and the traditional design residence, and verifies the effectiveness of the strategy of space optimization and building performance improvement.

1. Introduction

As a new construction method, prefabricated buildings have attracted more and more attention because of their high efficiency, environmental protection and reusability. Prefabricated buildings greatly shorten the construction period, reduce the environmental pollution caused by on-site construction and improve the construction quality by prefabricating building components in the factory and then assembling them on site [1]. Although prefabricated buildings have many advantages, they still face some challenges in practical application, the most prominent of which is how to realize efficient use of space on the premise of ensuring structural safety and how to improve the overall performance of buildings through design optimization. Spatial optimization is not only related to the residential comfort, but also directly affects the economy and sustainability of the building [2]. At the same time, the improvement of building performance, including structural safety, energy efficiency, indoor environmental quality, etc., is also an important indicator to measure the quality of prefabricated houses. Therefore, it is of great theoretical significance and practical value to conduct in-depth research on space optimization and building performance improvement in assembled residential design. The purpose of this study is to explore the spatial optimization strategy in the design of prefabricated housing, and analyze the influence of different design schemes on building performance.

2. Spatial optimization strategy

Space optimization aims to maximize the efficiency, comfort and adaptability of residential space under the constraint of prefabricated modules through refined, humanized and flexible design. The main strategies include the following aspects:

2.1 Modular and standardized design

Based on the basic functional modules (such as kitchen module, bathroom module and bedroom

  DOI: 10.25236/icacel.2025.152

module), the design follows the unified modular coordination principle. Reduce component specifications and increase universality and interchangeability. It is the premise of space optimization to realize large-scale production, reduce costs, reduce design errors and provide a foundation for flexible combination of different apartment types.

2.2 Variable and adaptive space design

Large bay and light partition wall system are adopted to reduce the restrictions of load-bearing interior walls [3]. Design a movable and foldable partition to realize the elastic separation of living, kitchen and other spaces. Meet the needs of different stages of the family life cycle (children's growth, home office, aging transformation), and improve the use efficiency and long-term value of space.

2.3 Composite function and integrated design

Through the composite function and integrated design, a variety of space functions are efficiently integrated, such as combining wardrobes, bookshelves and lockers with walls to create an overall storage system, and using bay windows to achieve dual purposes of leisure and storage [4]. At the same time, the integrated design of air conditioning, fresh air, lighting and other equipment with ceiling and wall not only improves the aesthetics of the space, but also enhances the coordination of the system. This design method aims at releasing more indoor net area, reducing the sense of crowding caused by furniture, making the space more neat and open, thus significantly improving the actual utilization efficiency of the space.

2.4 Fine size and ergonomic design

In the aspect of fine size and ergonomic design, the precise optimization of each functional area is emphasized according to the human scale and daily behavior streamline. For example, reasonably plan the "work triangle" of the kitchen-the distance between washing, cooking and storage, scientifically arrange the position of sanitary ware in the bathroom and ensure the minimum activity space to ensure comfortable use [5]. Its purpose is to minimize the waste of space and reduce the redundant area on the basis of ensuring functionality and comfort, and to use the saved space to improve the overall living quality, so as to realize a compact but not cramped ideal living experience.

3. Building performance improvement

The improvement of building performance focuses on improving the physical performance and service quality of houses through design optimization, material selection and system integration. The main methods are closely combined with the spatial optimization strategy.

3.1 Structural performance and safety improvement

BIM technology is used for accurate structural calculation and joint optimization design, so as to ensure the strength of the connection parts of precast members and the seismic performance of the whole building [6]. The use of high-strength lightweight materials such as lightweight aggregate concrete and steel frame can effectively reduce the weight of the building and improve the structural efficiency. Under the condition of factory high-precision manufacturing, it not only ensures the stability of component quality, but also makes the safety performance of assembled structure reach or even exceed that of traditional cast-in-place structure, which provides reliable technical support for realizing flexible spatial layout such as large bay and few load-bearing walls.

3.2 Energy saving and environmental protection performance improvement

In terms of energy saving and environmental protection performance, the green performance of buildings is comprehensively improved by integrating high-performance peripheral protection system and renewable energy technology. The prefabricated sandwich wallboard with heat preservation and insulation functions is adopted to effectively eliminate cold and hot bridges and significantly enhance the air tightness and thermal performance of the building; With high-performance energy-saving door and window system, natural lighting, transparent vision and thermal insulation requirements are taken into account [7]. In the early stage of design, the integration of renewable energy equipment such as solar photovoltaic panels and solar water heaters with the building facade or roof is considered, which greatly reduces the energy consumption of building operation, reduces carbon emissions and promotes the development of residential buildings in a low-carbon and sustainable direction.

3.3 Indoor environmental quality improvement

In order to improve the indoor environment quality, many technical means are adopted to optimize the comfort and health of living. In the aspect of acoustic environment, by setting sound insulation cushion in precast floor, selecting high-performance lightweight partition materials and optimizing equipment layout, the impact sound insulation ability of floor and the air sound insulation performance of wall can be effectively improved; In terms of light environment, the ratio of window to wall and the position and size of windows should be reasonably designed to ensure uniform and sufficient natural lighting and avoid glare interference; In terms of thermal comfort and air quality, relying on the high air tightness foundation of the building, the fresh air system with heat recovery function is integrated to realize the continuous renewal of indoor air and minimize energy loss [8]. These measures jointly create a quiet, bright and fresh indoor environment, and significantly improve the physical and mental health and quality of life of residents.

3.4 Intelligent operation and maintenance and long-term performance improvement

Through the strategy of intelligent operation and maintenance and long-term performance improvement, the building will be promoted to the direction of intelligent and sustainable operation and maintenance. In the production stage of prefabricated components, sensors are embedded and pipeline interfaces are reserved, which provides convenient conditions for installing smart home equipment such as intelligent lighting, environmental monitoring and security system in the later stage, and reduces the difficulty and cost of transformation [9]. This not only improves the flexibility and adaptability of the building in use, but also realizes the real-time monitoring and meticulous management of the building's operation state, which is helpful for timely maintenance and performance optimization, prolongs the overall service life of the building, and ensures its efficient, intelligent and stable operation state in the whole life cycle.

4. Empirical research

In this study, B-type apartment (experimental group) with new optimized design scheme in a prefabricated residential district was selected, and compared with A-type apartment (control group) with traditional design, so as to quantitatively evaluate its performance improvement in space efficiency, energy saving effect and indoor environment.

A-type apartment (traditional design) and B-type apartment (optimized design) with the same building area of 90 ㎡ are selected as the comparison objects, and a comprehensive evaluation method combining BIM model analysis, field measurement (including temperature and humidity, noise and illumination) and energy consumption simulation software is adopted to make quantitative comparison from multiple dimensions such as space utilization, energy consumption per unit area, indoor thermal comfort and indoor noise level.

By adopting the "composite function and integrated design", the effective use area of apartment B (the net area after deducting the occupation of walls and pipes) is significantly higher than that of apartment A. As shown in Table 1, under the same building area, the optimized design has gained an additional usable area of about 3.3 ㎡ for residents by reducing the wall thickness and the space occupation of pipelines, and the space efficiency has been effectively improved.

Table 1 Comparison of space utilization efficiency

Type of	Building	Traditional	Effective	Improveme

layout of an apartment	area (㎡)	effective use area (㎡)	usable area after optimization (㎡)	nt of area utilization rate
Unit A (control)	90	72.5	-	-
B apartment (experimental)	90	-	75.8	+4.6%

Through the software simulation of heating and cooling energy consumption throughout the year, it is found that the energy-saving effect of B-type apartment is remarkable because it adopts integrated external wall panels with thermal insulation (heat transfer coefficient K = 0.35 W/(㎡·K)) and high-performance doors and windows. Simulation data show that the total energy consumption per unit area of apartment B is about 26% lower than that of apartment A, and the energy saving effect is remarkable (Figure 1).

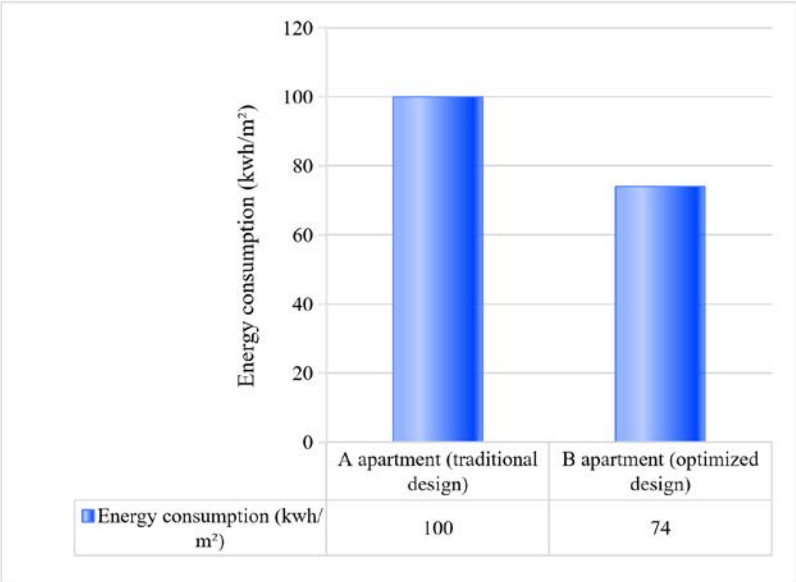

Figure 1 Comparison of building energy-saving performance

In the same external environment (outdoor temperature 35℃, outdoor noise 65dB), the living rooms of two units were measured. As shown in Table 2, because of the excellent air tightness and thermal insulation, the indoor thermal stability of apartment B is stronger and the comfort is higher. The integrated sound insulation structure effectively reduces indoor noise; The optimized window-wall ratio design improves the natural lighting effect.

Table 2 Comparison of indoor environmental quality

Evaluation index	A apartment (traditional design)	B apartment (optimized design)	Standard requirements
Indoor temperature fluctuation (summer)	±2.5℃	±1.2℃	-
Indoor noise level (daytime)	45 dB	38 dB	≤45 dB
Natural lighting illuminance (lx)	150	180	≥75

5. Conclusion

In this study, the space optimization and building performance improvement in the design of prefabricated housing are discussed in depth, and the corresponding strategies are put forward. Through the strategies of modular and standardized design, variable and adaptive space design, composite function and integrated design, and refined size and ergonomic design, the space utilization efficiency, comfort and adaptability are maximized under the constraint of prefabricated modules. The empirical study shows that the effective use area of apartment B with these optimized designs is about 3.3 ㎡ higher than that of apartment A with traditional design under the same construction area, and the space efficiency is improved by 4.6%. In addition, the total energy consumption per unit area of apartment B is reduced by about 26% compared with that of apartment A, and the energy saving effect is remarkable. In terms of indoor environmental quality, because of its excellent air tightness and heat preservation, B-type apartment has stronger indoor thermal stability, lower noise level and better natural lighting effect. These results show that through reasonable space optimization and building performance improvement strategies, the living quality and economy of prefabricated houses can be significantly improved, and the development of houses in a low-carbon and sustainable direction can be promoted.

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