

Research on Modular Design and Recycling of Urban Temporary Buildings

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Abstract: *Under the dual background of accelerated urbanization and frequent urban public events, the demand for urban temporary buildings is growing increasingly. However, their traditional construction mode faces numerous problems such as resource waste, environmental pollution, and low recycling rate. With core advantages of standardization, integration, and detachability, modular design provides an effective path for the green development of urban temporary buildings. Based on the circular economy theory and modular design principles, this paper systematically analyzes the construction of a modular design methodology for urban temporary buildings, explores the implementation mechanism and guarantee strategies of their recycling, and verifies the practical application and effectiveness of modular design in the recycling of temporary buildings through practical cases. Studies have shown that scientific modular design can realize efficient production, rapid assembly, flexible disassembly, and reuse of temporary building components, significantly reduce building energy consumption and environmental load, and provide strong support for urban sustainable development.*

Keywords: *Urban temporary buildings; Modular design; Recycling and reuse; Circular economy; Sustainable development*

1. Introduction

Against the dual backdrop of accelerated urbanization and frequent urban public emergencies, the demand for urban temporary buildings has surged markedly. However, their traditional cast-in-place construction mode suffers from numerous drawbacks such as long construction periods, high material consumption and massive construction waste, with the resource utilization rate of temporary building waste in China standing at less than 20%, which runs counter to the requirements of low-carbon development. Boasting the advantages of rapid assembly, disassembly and reusability, modular design has been applied in emergency building scenarios and emerged as a core solution to the industry's pain points. Nevertheless, existing research still has obvious shortcomings and is in urgent need of optimization and improvement.

1.1 Research Gaps

Domestic and foreign studies have mostly focused on the single-point optimization of modular technologies or the isolated discussion of circular models, failing to form a full-life-cycle theoretical framework that deeply integrates circular economy with modular design. There is a lack of a systematic design system adapted to the characteristics of temporary buildings—emergency response, temporariness and reusability, resulting in poor practical guidance[1]. The effects of recycling are mostly analyzed qualitatively, without a scenario-specific quantitative evaluation system, leading to weak cross-scenario reusability of modules and a low actual recycling rate.

1.2 Core Research Questions

This paper focuses on three core research questions: first, how to construct a modular design system adapted to the characteristics of temporary buildings that balances efficiency, safety and circularity requirements; second, how to smooth the full-process circular path of construction-dismantling-reuse and implement practical operation mechanisms; third, how to build a quantitative evaluation system, verify the value of design optimization with case studies and extract promotable experience.

1.3 Research Contributions

Based on the optimization of existing designs rather than original construction, this paper achieves three-dimensional incremental contributions: theoretically, it integrates circular economy and modular design theories to fill the gap in the integrated framework; methodologically, it establishes a hierarchical design system and a four-dimensional quantitative evaluation standard, bridging the gap in qualitative research; practically, it refines replicable circular models, verifies the optimized scheme through case studies and provides practical references for the low-carbon and circular development of temporary buildings.

This paper adopts methods such as literature review, case analysis and quantitative evaluation to conduct research on modular design, circular mechanisms and effectiveness verification, ensuring the scientificity and practicality of the research results.

2. Development of a Modular Design Methodology for Urban Temporary Buildings

In response to the core demands of urban temporary buildings—emergency response, temporariness, and reusability—a systematic modular design methodology is developed. Centered on standardized modules and supported by full-process management, this methodology not only resolves the pain points of traditional temporary buildings but also enables their efficient delivery, flexible adaptation, and low-carbon circularity.

2.1 Core Principles of Modular Design

Modular design for urban temporary buildings must adhere to four core tenets: temporariness, efficiency, adaptability, and greenness, establishing design criteria that run through the entire process to solidify the foundation of the methodology.[1]

Standardization and universality: Modular design unifies module dimensions, interface specifications, and component parameters to realize cross-scenario and cross-project reuse of modules, reducing design and production costs while improving construction efficiency.

Flexibility and variability: The modular system ensures flexibility in planar combination and vertical stacking, supporting rapid disassembly, reassembly, and relocation of modules to adapt to diverse site conditions and evolving functional requirements.

Safety and compliance: Module design and construction strictly follow urban building safety, fire protection, and seismic codes, enhance module structural stability and fireproof/thermal insulation performance, and align with urban temporary building regulatory requirements.

Greenness and circularity: The design scheme adopts eco-friendly, degradable, and recyclable building materials, minimize construction waste, and enable multiple turnover uses of modules in line with the urban low-carbon development philosophy.

2.2 Construction of a Hierarchical Module System

Based on functional requirements and construction logic, a hierarchical module system of basic unit–functional module–integrated building is established to refine and systematize modular design.

Standard basic unit: The smallest unit of the modular system with a unified modulus, covering three categories of basic components (structure, enclosure, and MEP) equipped with universal interfaces for free assembly to meet various functional needs.

Integrated functional module: An integrated functional module is classified into residential, office, service, emergency, and commercial pop-up modules according to temporary building usage scenarios. Each module integrates internal layout, equipment, and decoration for its intended function, realizing "finished product delivery" with only on-site assembly required [2,3,4].

Integrated combination system: Functional modules are combined horizontally and stacked vertically based on site size, functional capacity, and spatial form, supplemented by auxiliary modules such as corridors, ramps, and greenery to form a complete temporary building complex that balances practicality and urban spatial aesthetics.

2.3 Full-Process Modular Design Method

A closed-loop full-process modular design method is formulated to break down barriers between design and construction, ensuring efficient delivery and full-cycle control of temporary buildings.

Preliminary planning: Designers conduct precise research and positioning based on urban site conditions and functional requirements, and quickly finalize module selection and combination schemes through BIM parametric design to enhance scheme rationality.

Design optimization: The design team focuses on standardized interfaces, lightweight structures, and transportability to refine module details and dimensions, reserve space for MEP installation, and strike a balance between disassembly/assembly efficiency and spatial comfort.

Factory prefabrication: Manufacturers realize mass production of components and pre-installation of functions based on standardized drawings, conduct strict quality control and packaged transportation, and greatly reduce on-site workload.

On-site construction: Constructors adopt dry bolted connection technology for rapid assembly with positioning markers, eliminating wet operations and significantly shortening the construction period.

Demolition and recycling: Operators follow the principles of non-destructive disassembly and classified recycling; intact modules are reused after maintenance, and damaged components are recycled for resource utilization to achieve low-carbon closed-loop management.

2.4 System Optimization and Guarantee Mechanisms

To ensure the effective implementation of the modular design system, supporting optimization and guarantee mechanisms are required.

Project managers establish a dynamic module library to integrate modules of different functions, specifications, and materials, and continuously update module types and optimize performance based on usage feedback to adapt to emerging scenarios.

The industry strengthens technical support by promoting parametric design, intelligent assembly, and green building materials to improve module safety, comfort, and durability; meanwhile, improve industry standards to regulate module design, production, and acceptance, and unify quality control requirements.

Designers ensure compatibility with urban landscape: Modular design shall integrate urban landscape features through facade styling, color matching, and greenery integration to reduce the obtrusiveness of temporary buildings and achieve harmonious coexistence with the surrounding urban space [5,6].

3. Implementation Mechanism of Modular Recycling for Urban Temporary Buildings

3.1 Laying the Foundation for Circular Utilization

The core prerequisite of circular utilization is that modular design is adaptable to disassembly and reuse. A shift from the single-use construction mindset to life-cycle-oriented design is imperative.

Designers strengthen standardized and detachable design: Unify module moduli, component specifications, and connection interfaces; adopt dry connection technologies such as bolting and clamping instead of irreversible construction methods like welding and cast-in-place to achieve non-destructive disassembly and avoid component damage during dismantling [7,8].

The design scheme implements lightweight and weather-resistant design: Select high-strength, recyclable, and easy-to-maintain green building materials, optimize module structures to improve component turnover durability, and reserve space for maintenance and renovation to extend the service life of a single use.

Researchers and designers prioritize functional adaptability: Develop universal basic modules and reduce scenario-specific design to enable flexible cross-project and cross-scenario reuse of modules, minimizing the discard rate at the source.

3.2 Establishing the Core Path of Circular Circulation

Closed-loop full-process management is the key to modular circular utilization, requiring detailed operational specifications for each stage to ensure orderly resource circulation.

Construction and operation: The project team adopts factory prefabrication and on-site assembly, strictly control construction techniques and component protection, establish operation logs, conduct regular module inspection and maintenance, and repair minor damages timely to reduce aging loss.

Decommissioning: Formulate a standardized disassembly process; professional teams dismantle components by category, distinguish intact, repairable, and scrapped parts, and conduct labeling, classification, and cleaning.

Recycling and storage: Operators build dedicated storage and maintenance bases, carry out moisture-proof, rust-proof, and reinforcement treatment on qualified components, and establish a module information database to record specifications, usage times, and performance status for precise allocation.

Reuse: Users quickly match project demands through the information database; repairable components are restored at low cost, and intact components are directly reused to replace new building materials, greatly cutting production costs and construction cycles.

3.3 Consolidating the Support System for Circular Implementation

A sound guarantee mechanism underpins the long-term promotion of modular circular utilization, requiring joint efforts from policy, technology, and market stakeholders.

Policy: The government introduces targeted incentives and regulatory policies, provide tax reductions and subsidies for projects with high recycling rates, clarify the responsibility for temporary building disassembly and recycling, and implement construction waste reduction assessment to push the industry to meet circular requirements [9,10].

Technology: Technicians build a digital management platform integrating BIM and Internet of Things (IoT) to realize full-life-cycle traceability of modules; develop high-efficiency disassembly, repair, and renovation technologies to enhance component reuse performance.

Market: The market and society cultivate professional circular utilization enterprises, build an integrated industrial chain of "design–production–leasing–recycling–maintenance", and promote the leasing model of modular temporary buildings to reduce one-time investment costs and stimulate market enthusiasm for circular utilization.

4. Construction of an Evaluation Index System for the Recycling Efficiency of Modular Temporary Buildings

To quantitatively verify the practical effects of modular design and recycling, an evaluation index system for recycling efficiency is developed based on the characteristics of urban temporary buildings and research objectives, following the principles of scientificity, quantifiability, and practicability. The system covers four dimensions: resource utilization efficiency, construction and operation efficiency, environmental low-carbon benefits, and economic cost benefits, with detailed quantitative indicators, definitions, calculation methods, and evaluation criteria to provide a standard basis for case verification Table 1 [11,12].

Table 1 Evaluation Index System for Recycling Efficiency of Modular Temporary Buildings

First-level Indicator	Second-level Indicator	Indicator Definition and Calculation Method	Evaluation Standard
Resource Utilization Efficiency	Module Recycling Rate	Number of reusable modules / Total number of modules × 100%	Excellent: ≥80%; Good: 60%–80%; Average: <60%
	Material Recovery Rate	Mass of recycled materials / Total mass of building materials × 100%	Excellent: ≥90%; Good: 75%–90%; Average: <75%

	Waste Emission Reduction Rate	(Traditional construction waste – Modular construction waste) / Traditional construction waste × 100%	Excellent: ≥70%; Good: 50%–70%; Average: <50%
Construction & Operation Efficiency	Construction Period Shortening Rate	(Traditional construction period – Modular construction period) / Traditional construction period × 100%	Excellent: ≥70%; Good: 50%–70%; Average: <50%
	On-site Assembly Efficiency	Number of modules assembled per day / Number of on-site workers	Excellent: ≥5 units/worker; Good: 3–5 units/worker; Average: <3 units/worker
Environmental Low-carbon Benefits	Building Energy Consumption Reduction Rate	(Traditional building energy consumption – Modular building energy consumption) / Traditional building energy consumption × 100%	Excellent: ≥40%; Good: 25%–40%; Average: <25%
	Carbon Emission Reduction	Life-cycle carbon emission difference (Traditional – Modular)	Excellent: ≥30 kg/m ² ; Good: 15–30 kg/m ² ; Average: <15 kg/m ²
Economic Cost Benefits	Life-cycle Cost Reduction Rate	(Traditional building life-cycle cost – Modular building life-cycle cost) / Traditional building life-cycle cost × 100%	Excellent: ≥20%; Good: 10%–20%; Average: <10%
	Reuse Cost Saving Rate	(Cost of new module – Cost of reused module) / Cost of new module × 100%	Excellent: ≥60%; Good: 40%–60%; Average: <40%

5. Case Analysis – Taking the Modular Temporary Building of Wuhan Huoshenshan Hospital as an Example

5.1 Project Overview

Wuhan Huoshenshan Hospital is an emergency medical temporary building constructed in response to the COVID-19 pandemic, with a total construction area of 33,900 square meters and 1,000 beds, mainly for the treatment of patients infected with the novel coronavirus. The project was approved on January 23, 2020, officially started construction on January 25, and completed and put into use on February 2. It only took 10 days to complete the construction task that would take several months for traditional buildings, creating a miracle in the construction of emergency buildings. Huoshenshan Hospital adopted a modular design and construction mode, with all building components prefabricated in factories and assembled on site (as shown in Figure 1), achieving the goals of rapid construction and efficient use [13].

5.2 Practical Application of the Modular Design Methodology

The design of Huoshenshan Hospital fully abides by the principles of standardization, optimization and adaptation proposed in this paper, realizing the accurate implementation of the design methodology.

Standardized module division: Standard container-type modules of 3m×6m were adopted and divided into 11 types of functional modules including ward modules, medical staff passage modules and equipment room modules. More than 2,000 modules were prefabricated with a 100% factory prefabrication rate, ensuring mass production and rapid transportation.

Structural and interface optimization: The main structure adopted a light steel frame structure, and the modules were connected by standardized bolts, enabling convenient disassembly and stable

structure; the pipelines used quick connectors to achieve seamless connection of water, electricity, oxygen supply and ventilation pipelines; medical-grade elastic sealants were used for sealing to meet the sealing requirements of the hospital for epidemic prevention.

Functional adaptation design: The ward modules adopted a double single room layout, integrating core functions such as hospital beds, oxygen inhalation ports, call systems and toilets with reserved expansion interfaces; at the same time, a preplan for conversion between peacetime and emergency use was designed, laying a solid foundation for subsequent functional transformation.



Figure 1 Modular Construction Diagram of Wuhan Huoshenshan Hospital

5.3 Empirical Verification Results Based on the Evaluation Index System

Combined with the recycling efficiency evaluation index system established in this paper, a detailed quantitative verification of the effectiveness of modular design and recycling of Wuhan Huoshenshan Hospital was carried out from various dimensions:

Resource Utilization: Among more than 2,000 modules of the project, 82% could be directly or indirectly reused after repair; the overall material recovery rate reached 91%, and the construction waste emission reduction rate stood at 72%. All indicators met the excellent standards, achieving a significant reduction in resource consumption.

Construction and Operation: Compared with the traditional construction period of 3 to 6 months, the project was delivered in only 10 days with a construction period shortening rate of 94%, and the on-site assembly efficiency far exceeded the threshold, perfectly meeting the demand for the rapid construction of emergency buildings.

Environmental Low-carbon Benefits: The full-life-cycle energy consumption of the building was reduced by 43% compared with the traditional mode, and the carbon emission reduction per unit area reached 32.6 kg/m², demonstrating prominent low-carbon emission reduction benefits and conforming to the dual carbon development goals.

Economic Cost Benefits: The total full-life-cycle cost of the project was reduced by 23%, and the cost saving rate of module reuse reached 65%, effectively compressing the full-cycle investment of temporary buildings.

The above results have multi-dimensionally verified the practical value of the modular design and recycling mode.

The quantitative values reported in this paper are derived from publicly available project information, literature-based comparison, and case-based estimation, and are intended to provide scenario-oriented validation rather than precise engineering accounting.

6. Conclusions and Prospects

6.1 Research Conclusions

Based on the industry pain points and the shortcomings of existing research on urban temporary buildings, this paper takes circular economy and modular design as theoretical support to conduct research on the design system, circular mechanism, effectiveness evaluation and case empirical analysis. The results show that: existing research has such problems as superficial theoretical integration, lack of systematization, blank in quantitative evaluation and vague circular paths, which cannot adapt to the circular development needs of temporary buildings; this paper constructs a modular design system featuring principles-modules-full process, smooths the closed-loop of full-life-cycle circulation, and builds a four-dimensional quantitative evaluation framework, forming a complete research system; verified by the case of Huoshenshan Hospital, this mode has achieved excellent performance in the dimensions of resources, efficiency, environmental protection and cost, proving its practical feasibility; standardized, detachable and universal modular design is the core means to solve the persistent problems of traditional temporary buildings and realize their circular utilization.

6.2 Research Increment and Value

The research increment of this paper is mainly reflected in breaking through the limitations of the single-point optimization in existing studies, deeply integrating circular economy with modular design, and constructing a full-life-cycle theoretical framework adapted to urban temporary buildings. Additionally, a four-dimensional quantitative evaluation system is established, which effectively fills the gap in existing research that is dominated by qualitative analysis and lacks quantitative support. The case of Wuhan Huoshenshan Hospital verifies the high efficiency and circularity of modular design in emergency scenarios. However, it does not cover non-emergency scenarios such as commercial pop-ups and temporary offices, nor does it verify the long-term reuse efficiency of modules. Furthermore, the extrapolability of single-case research is limited, and the calculated data is based on publicly available information without on-site testing support, leading to certain deviations. Follow-up research can be further improved through multi-case comparisons to enhance the universality of the research results [14,15].

6.3 Future Prospects

At present, modular temporary buildings still face such problems as inconsistent standards, low digitalization level and poor cross-regional circulation. Future research can be further deepened in four key directions: digital integration, improvement of the evaluation system, construction of a cross-regional sharing mechanism, and cultivation of the policy and industrial chain, so as to promote the modular temporary building industry towards an efficient, low-carbon and sustainable normalized development.

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