Research on a Complete Set of Technologies for Assembled Residential Buildings with Steel-Structure Based on House Type Modularization and Component Standardization

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Abstract. The industrialization of assembled buildings with steel-structure is a major strategic demand in China nowadays in terms of the development of life cycle green buildings, the transformation and upgrading of housing industrialization, and the solution to steel industry overcapacity. Steel residential buildings have several advantages over traditional constructions: lightweight, good seismic performance, wind resistance, a high degree of prefabrication, rapid construction speed, and convenient construction; these are the factors promoting its rapid development in recent years. Based on the concept of house types modularization and parts standardization, the authors propose a series of standardized house types for assembled buildings with steel-structure, establish numerical evaluation method and optimization method of standardization rate based on Building Information Modelling(BIM). In this regard, we develop and rank performance criteria for assembled buildings by calculating the rate of prefabrication. Also, this study develops a complete set of technologies for the building envelope system, facility and pipeline system, and interior decoration system that matches with the structure system. Meanwhile, we apply the research results to engineering projects in practice and examine their applications. This research has proved useful for architects by providing a set of equations to evaluate the number of standardized parts.

Keywords. Assembled buildings, steel structure, standardization, refinement, integration.

1. Introduction

A prefabricated building is a type of construction which are assembled on-site with factory-built components. In terms of the material of the main structure, it contains three categories: prefabricated concrete structure, prefabricated steel structure, and prefabricated wood structure. Compared with the concrete structure, the prefabricated steel structure shows more economic value and social benefits. Since the 18th National Congress of the Communist Party of China has defined the goal of ecological civilization, the government has issued guidelines for implementation on steel building application pilots and increasing the proportion of prefabricated steel buildings.

Ministry of Housing and Urban-Rural Development (MOHURD) successively issued national and industry standards for assembled buildings with steel-structure, leading to perfections of steel structure technical systems. In 2019 MOHURD launched pilot projects of the prefabricated building with...
steel-structure, and seven provinces received approval for implementation (Hunan, Shandong, Henan, Sichuan, Jiangxi, Zhejiang, Qinghai). Meanwhile, MOHURD has steadily progressed the application of steel buildings in various housing construction projects, including indemnificatory housing, relocation for poverty alleviation and new rural construction, rural reconstruction of dilapidated housing, and pilot anti-seismic rural housing.

However, the promotion of assembled buildings with steel-structure in China still has several problems to be solved:

- Mismatching between the frame structure system and the existing plane layout;
- Weak relationships between the building envelope system and the major structure;
- Low assembled rate;
- Insufficient technology integration and a low degree of synergy among the major bodies of the industrial chain.

China’s steel structure construction accounts for only 8% of the civil building structure system currently, in contrast to 20% to 35% in developed countries abroad [1], which means there is great potential for development in this area.

2. Standardized House Type Design Based on “Basic Room” Modules

Design standardization is the prerequisite for the development of steel-framed housing. According to previous studies [2-3] on modular buildings, Non-standardization introduces a series of negative impacts, such as an increase in the number of component types, results in a higher cost per quantity of steel, rising labor costs, and longer construction periods. In recent years most assembled buildings with steel-structure built in China are based on a cast-in-place system, making it difficult to form a continuous structural column network due to the irregular plane, thus failing to give full play to the advantages of the steel structure. Besides, there are numerous exposed beams and columns inside the house, which incur extra cost to hide them and compromises aesthetics. To adapt to the mechanical properties of the steel structure system, the main design principles are as follows: following the principle of modular coordination, fewer specifications, more combinations (figure 1).

- Planes should be regular to reduce irregular shapes. The unit planes with arbitrary deep grooves and offset cores in the cast-in-place system should be avoided.
- The columns should be arranged continuously along the X-axis and Y-axis as far as possible to form a regular column network and a direct and efficient transmission of horizontal force.
- Fixed functions should be centrally organized, with kitchens and bathrooms centrally arranged to facilitate the processing of structural drop drainage and the relative concentration of equipment and piping.

Figure 1. Standardized household design module decomposition and combination diagram.
Under the above principles, to exploit the force advantages of the steel components, we reorganize the house type with the “Basic Room” as the basic module (figure 2). Compared to the traditional combination of kitchen module, bathroom module, bedroom module, study module, and dining room module, the “Basic Room” module rounds up the small spaces to better fit the structure’s standard column span spaces.

**Figure 2.** Standardized house design with standard room as the basic space module.

The different “Basic Room” space modules can be freely combined into apartment buildings and tower buildings standard floor combination planes such as 1 unit of 2, 1 unit of 4, 1 unit of 6, 1 unit of 8, etc., and can form a combination plan of gallery buildings standard floor for 1 unit of 10 or more (figure 3).

**Figure 3.** Standardized layer composition design based on “Basic Room” modules.

At the same time, the “Basic Room” module can be used as the elementary unit of the residential facade design. By controlling the combination and variation of the “Basic Room”, a rich facade effect can be created (figure 4).

**Figure 4.** Standardized facade design based on “Basic Room” modules.

To evaluate the ventilation condition of the house, Phonenics, a software based on the principle of computational fluid dynamics (CFD), was used to simulate and analyze the wind environment in the
design (figure 5), and the results show that the indoor ventilation is good under the year-round prevailing wind conditions in Chengdu, creating an agreeable living environment.

![Figure 5](image_url)

**Figure 5.** Residential wind environment simulation based on CFD software.

3. Numerical Evaluation and Optimization of Component Standardization Rate Based on BIM Model

Regarding the standardization of assembly buildings, some studies investigated the use of modular building components and standardized parts platforms. Thajudeen et al. [4] studied a set of standard components as a high level of customization. Also, Geldermans [5] bring up the concept of “Circular Building” claimed the value of the building part is at the intersection of intrinsic and relational properties defined by multiple parameters. Mohammad Kamali et al. [6] developed an assessment framework of life cycle sustainability performance for modular buildings. Moreover, researchers explored synergies between Lean Production Principles and Building Information Modeling (BIM) functionalities [7-8]. Through a comprehensive literature review, we have identified approaches to establish criteria for evaluating standardization.

In contrast, at present, domestic researches on the standardized design of assembly buildings are mostly limited to the qualitative analysis of “fewer specifications, more combinations” with relatively few quantitative studies. Wen and Liu [9] proposed a method for calculating the repetition rate of parts and components to measure the proportion of standardized parts and components selected in the same category as well as in a single building. Ming Ye [10] proposed a scoring rule for standardized designs that constrains the ratio of the total number of the three (one) most reusable specification components to the total number of similar components in each category. The rule requires that the three most reusable parts, such as prefabricated beams, columns, and wall panels, account for 50% of the total number of units. It also requires 60% of the total number of components in the three most reusable sizes, such as prefabricated stairs and prefabricated laminated panels. Prefabricated stairs with the most reusable of one specification accounted for at least 70% of the total number of units, while prefabricated internal partition panels, prefabricated balcony panels should make up no less than 50% of the total. Wang et al. [11] proposed the “standardization rate” as the binding optimization data of the relationship between the type and number of components in a prefabricated building design process, and the study also analyzed the role and influence of the standardization rate as the optimization assessment index system for the design of an assembly wood structure. However, none of those studies has fully addressed the role of standardization in the integration between the design and assembly of prefabricated building components.

To accurately control the overall assembly rate of buildings to save cost and construction time, a statistically-based algorithm is used to rate the assembled building (figure 6), with evaluation thresholds, are divided into several subdivisions. The algorithm automatically screens the three main composition system of the building: the major structure system, the envelope system, and the facility and piping system, and removes any parts that do not meet the criteria, so that the overall assembly rate of the building remains within a reasonable range (table 1).
Table 1. The statistically-based algorithm output.

| Evaluation Criteria                  | Evaluation Requirements | Evaluation Scores | Lowest Scores |
|--------------------------------------|-------------------------|-------------------|--------------|
| Major Structure System               | Columns, supports, bearing walls, ductile, Wall panels, and Other vertical members. | 35%~80% | 20~30
| And Partition System                | Components such as Beams, Slabs, Stairs, Balconies, Air conditioning panels, etc. | 70%~80% | 10~20
| Envelope And Partition System       | Non-bearing walls, Non-envelope walls | >80% | 2~5
| System                              | Thermal insulation Partition | 50%~80% | 5
| And Partition                       | Non-masonry Partition | >50% | 2~5
| System                              | Integrated Decoration | 50%~80% | 6
| Decoration                          | Full Decoration | - | 6
| Decoration                          | Non-wet Floor, Non-wet slab | >70% | 6
| Facility and Pipelines Systems      | Integrated Kitchen | 70%~90% | 3~6
| Systems                             | Integrated Bathroom | 70%~90% | 3~6
| Systems                             | Pipe detached From structure | 50%~70% | 4~6

Since several previous studies investigated the relationship between architecture and intelligent manufacturing (Puscasu Samuel [12] and Niknam [13] made progress in this field, we introduced standardized calculation methods commonly used in the mechanical manufacturing industry. And the standardized rate is named as \( \rho_1 \).

When based on a single part type, the standardized rate \( \rho_1 \) for that type of part is calculated as follows.

\[
\rho_1 = \frac{a}{c} \%
\]  

(1)

\( A \) is the number of standardized parts, and \( C \) is the total number of parts of the three specifications that are most frequently reused.

According to equation 1, we can calculate the standardization rate for each type of part (table 2).

Note: This is an open table. When other assembly technologies are used, the number of standardized parts for that technology and the number of parts for headquarters can be added to the subdivision.

To calculate the total standardized rate for a single building, the standardized rate \( \rho_2 \) for a single building can be derived from table 1 as follows.

\[
\rho_2 = \frac{\sum_{i=1}^{n} a_i k_1 k_2 \%}{\sum_{i=1}^{n} c_i}
\]  

(2)

For the entire project, when the parts are not limited to use in a single building, but are also reused in other buildings throughout the project, the standardized rate \( \rho_3 \) for the entire project can be derived from equations (1-2) as follows.
It should be noted that the choice of the structure system has a remarkable impact on the standardization rate of the parts, and it is necessary to multiply the correction factor $k$ when adopting different structure systems. In the calculation of the standardization rates of three major categories of parts, namely, major structure parts, envelope parts, and interior facility piping components, a particularly large quantity of a single category of components often skew on the results of the pull-through calculation. Therefore, we recommend that the standardization rates of the components be calculated separately (figure 7). For steel structure buildings, it is essential to study the standardization rate of the main structural components to control the cost, so we focus on the automatic statistics and calculation of the standardization rate of the component types and quantities based on the BIM model, and the workflow is shown in the figure below.

| Classification          | Name                                      | Num of Standard Components | Num of Non-standard Components | Total Num  | $\rho_1$ |
|-------------------------|-------------------------------------------|----------------------------|--------------------------------|------------|---------|
| Components of the main structure | 1: Prefabricated Columns                  | $a_1$                      | $b_1$                          | $c_1$      | $a_1/c_1\%$ |
|                         | 2: Prefabricated Beams                    | $a_2$                      | $b_2$                          | $c_2$      | $a_2/c_2\%$ |
|                         | 3: Prefabricated panels                   | $a_3$                      | $b_3$                          | $c_3$      | $a_3/c_3\%$ |
|                         | 4: Prefabricated balcony panels           | $a_4$                      | $b_4$                          | $c_4$      | $a_4/c_4\%$ |
|                         | 5: Prefabricated air conditioning panels   | $a_5$                      | $b_5$                          | $c_5$      | $a_5/c_5\%$ |
|                         | 6: Prefabricated Stairs                   | $a_6$                      | $b_6$                          | $c_6$      | $a_6/c_6\%$ |
|                         | 7: PCF concrete formwork for exterior walls | $a_7$                    | $b_7$                          | $c_7$      | $a_7/c_7\%$ |
| Components of the building envelope | 8: Precast Concrete Wall Panels          | $a_8$                      | $b_8$                          | $c_8$      | $a_8/c_8\%$ |
|                         | 9: Autoclaved aerated concrete facade systems | $a_9$                  | $b_9$                          | $c_9$      | $a_9/c_9\%$ |
|                         | 10: Integrated exterior wall systems with lightweight steel studs | $a_{10}$ | $b_{10}$ | $c_{10}$ | $a_{10}/ c_{10}\%$ |
|                         | 11: Integrated Kitchens                   | $a_{11}$                   | $b_{11}$                       | $c_{11}$   | $a_{11}/ c_{11}\%$ |
| Interior and plumbing components | 12: Integrated Bathroom                  | $a_{12}$                   | $b_{12}$                       | $c_{12}$   | $a_{12}/ c_{12}\%$ |
|                         | 13: Prefabricated Ceiling                 | $a_{13}$                   | $b_{13}$                       | $c_{13}$   | $a_{13}/ c_{13}\%$ |
|                         | 14: Dry Process Flooring                  | $a_{14}$                   | $b_{14}$                       | $c_{14}$   | $a_{14}/ c_{14}\%$ |
|                         | 15: Interior partition panels in assemblies | $a_{15}$ | $b_{15}$ | $c_{15}$ | $a_{15}/ c_{15}\%$ |
| Total                   |                                            | A                          | B                              | C          | A/C\%   |

$$\rho_3 = \frac{\sum_{i=1}^{n} A_i k_i}{\sum_{i=1}^{n} C_i} \%$$
Figure 6. BIM model-based component standardization rate calculation flow.

Figure 7. Statistical charts for standardization of steel structural components.

Substituting statistical data into equation (1) yields:

\[
\rho = \frac{67+28+10+28+2+2}{67+28+4+2+10+28+2+2} \times 100\% = 95.8\%
\]  

(4)

The calculation of the standardization rate has a positive impact on the standardization of components. Building projects with an overall standardization rate of less than 50% should be prohibited from using assembly technology or should be ordered to redesign if they do not pass the evaluation. Besides, due to the large differences in the types and numbers of parts in buildings of different sizes and structure systems, the numerical differences in the standardization rate will be large, and a more detailed evaluation criterion, i.e., the set value of the correction factor k, is needed for further in-depth analysis in actual engineering applications.

4. Refined and Variable Design of Prefabricated Decoration

According to the “Assessment Standards for Prefabricated Buildings”, the current domestic prefabricated building decoration accounts for as much as 40%, and steel-framed houses are suitable for a housing system that separates the supporting body and infill body, i.e., SI system. The interior components mainly refer to all residential components in the “infill body” other than the outer walls, including wall system, ceiling system, floor system, integrated kitchen, integrated bathroom, etc. (figure 8). With the design of separating the piping from the main structure, the walls, floor, and ceiling are all separated from the main structure and become piping channels. The floor heights and decoration styles of the houses are determined according to the structure selection and interior installation methods (figure 9).

Figure 8. Major interior parts.
The wall adopts a light steel keel partition, which has the characteristics of lightweight, high strength, fireproof, and has the advantages of space-saving, reversible assembly, mobile reset, easy recycling, etc. It solves the problems of cracking, falling off, mold, and water leakage caused by traditional wet work on the wall. For parts with higher requirements for sound insulation and security, the light board wall body and veneer wall can be used to achieve integration of the wall with electromechanical pipes and interior decorative surfaces.

The roof adopts the assembled ceiling, which is suitable for kitchen and bathroom space, and the calcium silicate composite roof panel has the characteristics of high density, fireproofing, waterproofing and durability, and is easy to be dismantled and refurbished, which solves the problems of the traditional ceiling, such as easy deformation, cracking and peeling off.

The integrated kitchen comprises all kinds of kitchen products, equipment piping, and operation functions. It is more reasonable and scientific in design and technology, more efficient in construction, and lower in cost than the traditional kitchen. The integrated bathroom will be prefabricated in the factory with sanitary ware, equipment piping, wall panels, waterproof chassis, roof panels, etc. Then, it will be packaged and transported to the construction site for assembly. The integrated bathroom has been widely used abroad, and our country has also been trialing it in recent years.

Figure 9. Schematic representation of interior decoration with SI system.

With the continuous development and progress of society, people’s demand for quality of life is increasing, and they have detailed requirements for decoration. Refinement design should be client-oriented, and the implementation should be of high-quality and high-precision. The demands of families in different stages of living are deduced from simulations, functional space is exchanged, and the adaptability to the dynamic process of use is realized by fine design. Using the 115 m² standard plan layout as the basic module, we can develop the decoration design of typical life stages such as single, couple, family of three, three generations, and age-appropriate residence (figure 10). The SI system can be perfectly adapted to the changing needs of the residents over time and compensate for the redundancy and inadequacy of space in the house type.

Figure 10. Variable space design to adapt to changing occupant needs.

5. Integrated Design of Architecture, Structure, Electromechanics and Decoration
The core of the integrated design of assembled buildings is the SI system. It separates the main structure of a house with different lifespans from the interior decoration parts and equipment piping
and sets up an independent and centralized piping space so that when the interior parts and equipment piping that have reached the end of their service life are replaced, they do not affect each other or damage the building structure. The structure is designed to provide large and flexible interior space, allowing residents to divide the interior space according to their own needs, changing the size and layout of the rooms to meet different needs at different times.

With the pipeline detached approach, non-wet flooring, non-wet ceiling, and veneer walls are used to solve problems such as on-site grooving of electromechanical pipelines, precise pre-positioning of electromechanical pipelines within the building structure, collision of pipelines, and hiding beams and columns (figure 11). The public area is equipped with tube wells centrally arranged for electromechanical piping, which facilitates dismantling and maintenance and greatly reduces renovation costs.

**Figure 11.** Schematic representation of SI-based electromechanical pipeline distribution.

The promotion of BIM technology plays an important role in improving the productivity and engineering quality of assembled buildings. The standardized design based on BIM technology can effectively improve drawing efficiency and constructability (figure 12). By breaking the traditional two-skin design and construction model through EPC, the integrated design of architecture, structure, electromechanics, and decoration, as well as the information and intelligent management of production, construction, operation, maintenance, and recycling throughout the life cycle can be realized more effectively to improve efficiency and save costs.

**Figure 12.** Integrated design of the entire profession using BIM technology.

6. **Conclusion**
Policy support, industrialization demand, and the increase in steel production have greatly promoted the development of steel structure construction. China’s steel production has ranked first in the world, and it has developed strong strength in steel structure production, processing, and installation, laying a solid foundation for the development of the steel structure building industry.
At present, the cost of steel structure building is slightly higher than that of cast-in-place concrete by 5% to 10%. Through standardized design, mass production, and large-scale supply, we try our best to reduce the cost and at the same time pay attention to the improvement of housing yield, fire prevention, seismic safety, and durability, to promote its development through excellent quality and high-cost performance.

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