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Research article

# A Value Engineering Approach for Structural System Selection of Prefabricated Buildings

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## Abstract

The development and implementation of prefabricated buildings has been accelerating rapidly in recent years due to the ongoing revolution in the construction industry. Among different stages and aspects in completing a prefabricated building project, the selection of the prefabricated structural system is a crucial step because it has direct influence on both the cost and usage of the building. This paper proposed a structural system selection model for five commonly used prefabricated buildings structures based on value engineering's value coefficient analysis ranking which took both life cycle cost coefficient and functional coefficient into consideration. The proposed model aims at providing an innovative approach assisting early decision making on the selection of structural systems for project stakeholders. The case study provided in this paper demonstrated the feasibility and effectiveness of the proposed model. With proper implementation, the proposed approach can also promote the development of prefabricated buildings due to their cost and value advantages.

## Introduction

The urbanization development is still at high speed globally, as a relatively new and more sustainable building type, the prefabricated building (PCB) has become increasingly popular in the construction industry. For PCBs, there are various types of structural systems and each has different cost and functional characteristics. Selecting appropriate structural system of PCBs that will satisfy the owner's and end user's needs is one of the most crucial decisions of the project, because it determines or directly affects the basic structure, cost, construction and the actual usage of the building. Thus, to further promote the usage and better development of PCBs, this paper developed a value engineering based structural system selection model that can consider both their costs and functional factors from life-cycle perspective for PCBs.

A comprehensive literature review was conducted on literatures that are related to PCBs and their structural system selections in the globe. This literature are categorized into four categories, including fire resistance of prefabricated components [1], life cycle design of prefabricated buildings [2], emission of greenhouse gases [3] and life cycle energy consumption of prefabricated buildings [4]. Jin analyzed studies conducted in the past decade that focused on the development of prefabricated buildings overseas and provided the conclusion that the main focuses are construction performance of prefabricated buildings [5,6] application of prefabricated building management [7,8] and analysis of the factors influencing the development of prefabricated buildings [9,10]. Other studies are limited to economic benefit evaluation [11,12] information management based on BIM [13,14] and seismic behavior of prefabricated components [15]. Also, most of the related research used concrete structures as the research objects [16,17]. Some other studies were about the application of prefabricated buildings structural systems [18,19], design of prefabricated buildings structural systems [20,21] and economic performance of prefabricated buildings [22].

Past research has indeed enriched the research of prefabricated buildings, but few studies were conducted on the selection of structural systems of prefabricated buildings, especially took both cost and functional factors into consideration. Considering its importance, this paper proposed a structural system selection model for five commonly used prefabricated buildings structures based on value engineering's value coefficient analysis ranking which took both life cycle cost coefficient and functional coefficient into consideration. A case study is also provided in this paper to demonstrated the feasibility and effectiveness of the proposed model.

## Structural System Analysis of Prefabricated Buildings

Compared to traditional construction methods and building types, prefabricated buildings transferred a lot of on-site works to factories for prefabrication. For example, floors, wallboards, stairs and balconies can all be prefabricated and transported to the construction site. Then, reliable connection members are used to install the components [23]. Mainly used prefabricated building structures include concrete structure, steel structure, wood structure and mixed structure. In this section, the characteristics of five commonly used prefabricated structures are compared [24-29] and is shown in Table 1.

**Table 1:** Comparison of structural characteristics of five fabricated concrete structural systems.

| | Fabricated frame Structural System | Fabricated frame Cast-in-Situ Shear Wall Structural System | Prefabricated Shear Wall Structural System | Double Side Composite Plate Shear Wall Structural System | Externally Hung and Internally Cast PCF Shear Wall |
|---|---|---|---|---|---|
| Prefabricated components | Columns, composite beams, exterior walls, composite floors, etc | Frame columns, beams, shear walls, peripheral wall panels, internal partitions, etc | Shear walls, composite floors, stairs, interior partitions, etc | Shear wall, composite floor, stair, balcony, interior partition, etc | Exterior wall, laminated floor, balcony, stair, laminated plate, etc |
| Seismic performance | 7 degrees | 6-8 degrees | 6-8 degrees | 7 degrees | 6-8 degrees |
| Construction difficulty | higher | higher | higher | Lower | Lower |
| Construction efficiency | Lower | Lower | Lower | higher | higher |
| Connection mode | Dry connection+wet connection | Dry connection+wet connection | Effective cast-in-place | Joint bar connection | Traditional cast-in-place |
| Assembly rate | 15%-65% | 40%-85% | 30%-80% | Up to 40% | 15%-20% |
| Prefabrication rate | 20%-80% | 45%-90% | 40%-85% | Up to 50% | 15%-35% |
| Construction cost | higher | higher | higher | Lower | Lower |
| Applicable height | Below 50m | High rise, super high rise | High rise | High rise, super high rise | High rise, super high rise |
| Applicable buildings | Apartments, hotels, schools, industrial buildings,etc | High rise office buildings, high-rise hotels, apartments, etc | Commercial housing, affordable housing, etc | Commercial housing, affordable housing, etc | Commercial housing, security housing, office buildings, etc |
| System characteristics | High degree of industrialization, good freedom of internal space, and exposed indoor beams and columns | Small quantities and regular shape at node connection are conducive to energy conservation | High degree of industrialization, complete room space, no exposed beams and columns, general spatial flexibility | High industrialization, fast construction speed, simple connection, light component weight, low precision requirements, etc | The vertical load-bearing structure is cast-in-situ, and the external wall hanging plate does not participate in the force, and it is often used in conjunction with the large steel formwork construction |

## Structural system Selection Model of Prefabricated Buildings

Proper application of prefabricated buildings requires simplicity of construction operation, feasibility of production as well as basic architectural aesthetics. Thus, for different projects, the design concept and structural system selection should take site conditions, owner's needs, safety, cost and functions into consideration to ensure successful application of prefabricated building technologies on the project.

## Methodology

Prefabricated buildings can also be considered as special merchandise that requires long time and complicated resource support to produce. Thus, cost performance, especially life-cycle cost performance needs to be considered. In ordinary construction project management, the traditional cost reduction process often lacks consideration of the "whole picture" from design to construction and to the actual usage of the building. In contrast, value engineering cost reduction process comprehensively considers cost, function, value and users' benefits. Thus, using value engineering to evaluate the structure selection of prefabricated buildings has significant advantages over traditional approaches.

Although prefabricated buildings often take longer time and has larger demand in the design and cost estimation phase, they have significant time and cost savings in the construction phase [30]. Also, life-cycle cost analysis should be implemented to take complicated cost factors into consideration and to provide a more comprehensive perspective for the project. Thus, in this study life-cycle cost was used for the buildings cost coefficient analysis.

Then, for value engineering, commonly used value coefficient calculation methods include direct scoring method, forced scoring method, multiple ratio method, analytic hierarchy method, entropy weight method, multi-objective maximum distance method and functional system scoring method [31]. Among which, the force scoring method, especially its 0 to 4 scoring method is best suitable for this study because it fits the fact that prefabricated buildings have relatively less functional indicators and they are not significantly dependent to each other. Thus, the 0 to 4 scoring method was used for the building's functional coefficient analysis.

## Model development for structural system selection of prefabricated buildings

### Theoretical basis of value engineering

Value engineering was firstly developed by design engineer Lawrence D. Miles of General Electric in the United States in 1947 when he was studying raw material substitutes. In 1954. this method was implemented by the United States Navy and was named value engineering. The first-time value engineering was introduced in China was in 1979, with decades of application, it is now widely used in machinery, chemical, construction, metallurgy and other industries.

In value engineering, value means the measurement of the something's benefits. Higher value means that the product, decision, measure or object has more benefits or functions over its cost and is more efficient. Function is the performance or use, in essence, is the use value of the product. In this paper, it is the goal achieved through different structural systems. At last, the cost means the total expenditure of the products in the whole life cycle. When calculating the full life cycle of a building, there is also the cost of demolition and recovery, that is, the full life cycle cost C=production cost $C_1$+use cost $C_2$+demolition and recovery cost $C_3$. Thus, the value can be calculated as the ratio between its functions and cost, as shown in equation 3-1:

$$V = F \div C$$

Where V is the value, F is the function and C is the cost.

Value V: refers to the ratio of the function of an object to its total cost. The value studied in this paper represents the economic benefits of the product.

### Life cycle cost analysis of prefabricated buildings

The life cycle of prefabricated buildings refers to the whole process of prefabricated buildings from conception to decision-making, from design to construction, from use to maintenance, and finally to scrapping. The life cycle cost is any cost happens within the whole life cycle, this includes recurring or one-time expenses, as well as indirect or direct expenses [32]. The LCC can be divided into different categories as shown in Figure 1.

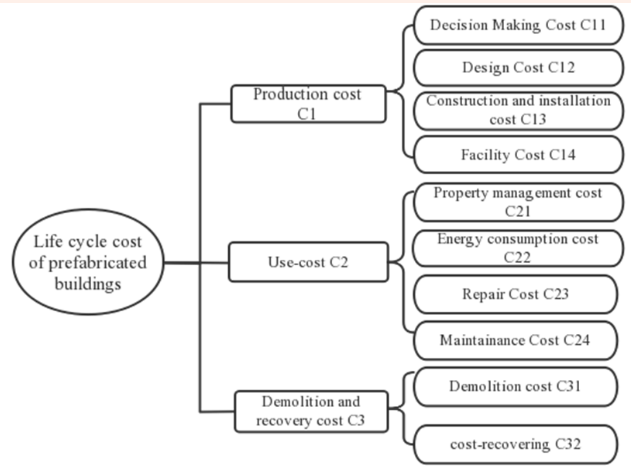


**Figure 1:** Life cycle cost of prefabricated buildings

The calculation formula of life cycle cost of prefabricated buildings based on time value is :

$$C = C_1 + C_2 r_1 + C_3 r_2 \qquad (3-2)$$

$$C_1 = C_{11} + C_{12} + C_{13} + C_{14} \qquad (3-3)$$

$$C_2 = C_{21} + C_{22} + C_{23} + C_{24} \qquad (3-4)$$

$$C_3 = C_{31} - C_{32} \qquad (3-5)$$

Where C is the total life cycle cost of prefabricated buildings; $r_1$ and $r_2$ are cash conversion coefficients

### Selection and analysis of functional indicators of prefabricated buildings

When analyzing and selecting the functional indicators of the prefabricated building structural system, after reviewing existing literatures, three functional dimensions, include construction feasibility, environmental effect and brand effect are selected [33,34]. Figure 2 shows the prefabricated building functional indicator system used in this study.

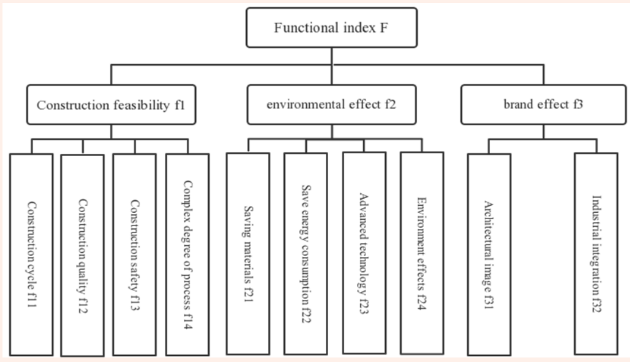


**Figure 2:** Functional index system of prefabricated buildings.

By analyzing the functional indicators of the prefabricated buildings in Figure 2, the indicators are compared in pairs using the 0 to 4 scoring method based on the scoring principles shown in Table 2.

**Table 2:** Scoring principle of 0-4 scoring method.

| Meaning | Score of $F_m$ | Score of $F_n$ |
|---|---|---|
| Compared with $F_n$, $F_m$ is less important than $F_n$ | 0 | 4 |
| Compared with $F_n$, $F_m$ is less important than $F_n$ | 1 | 3 |
| $F_m$ is as important as $F_n$ as $F_m$ | 2 | 2 |
| $F_m$ is more important than $F_n$ | 3 | 1 |
| $F_m$ is more important than $F_n$ | 4 | 0 |

The 0-4 scoring rule in Table 2 is used to determine the weight of prefabricated building function indicators. The results after expert scoring are shown in Table 3.

**Table 3:** Weight coefficient of function index of prefabricated building.

| Function | f11 | f12 | f13 | f14 | f21 | f22 | f23 | f24 | f31 | f32 | Score | Weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $f_{11}$ | × | 2 | 1 | 3 | 3 | 3 | 2 | 2 | 3 | 2 | 21 | 0.117 |
| $f_{12}$ | 2 | × | 2 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 26 | 0.144 |
| $f_{13}$ | 3 | 2 | × | 3 | 4 | 3 | 2 | 2 | 3 | 3 | 25 | 0.139 |
| $f_{14}$ | 1 | 0 | 1 | × | 3 | 3 | 2 | 2 | 3 | 3 | 18 | 0.100 |
| $f_{21}$ | 1 | 1 | 0 | 1 | × | 1 | 2 | 2 | 2 | 2 | 12 | 0.067 |
| $f_{22}$ | 1 | 1 | 1 | 1 | 3 | × | 3 | 2 | 2 | 2 | 16 | 0.089 |
| $f_{23}$ | 2 | 2 | 1 | 2 | 2 | 1 | × | 2 | 2 | 2 | 16 | 0.089 |
| $f_{24}$ | 2 | 2 | 1 | 2 | 2 | 2 | 2 | × | 3 | 3 | 19 | 0.105 |
| $f_{31}$ | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | × | 3 | 14 | 0.078 |
| $f_{32}$ | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | × | 13 | 0.072 |
| total | | | | | | | | | | | 180 | 1 |

After determined the weight coefficient of prefabricated buildings' functional indicators, the experts scoring method (0 to 10) was used to rate the ten functions for five different structural systems of prefabricated buildings including fabricated frame with cast-in-situ shear wall structure, fabricated frame structure, fabricated shear wall structure, double-sided laminated plate shear wall structure, and externally hung and internally cast PCF shear wall structure. In this scoring process, higher score means higher degree of membership, so the final functional coefficient score of each system is obtained.

## Model selection steps of prefabricated building structural system

When using value coefficient method to optimize the selection of prefabricated building structural systems, the following assumptions and steps should be performed:

1. If the functional factor coefficient of alternative m is $f_{m1}$, $f_{m2}$..., $f_{m10}$ and the score of each function is $p_{m1}$, $p_{m2}$...$p_{m10}$, then the function coefficient of alternative m is Fm as shown in formula 1

$$F^m = \frac{\sum_{r=1}^{10} p_{mr} f_{mr}}{\sum_{m=1}^{n}\sum_{r=1}^{10} p_{mr} f_{mr}} \quad \cdots \textit{Formula } 1$$

2. If the cost of alternative m is Cm, the cost coefficient of alternative m is $C_m$ as shown in formula 2

$$C^m = \frac{C_m}{\sum_{m=1}^{n} C_m} \quad \cdots \textit{Formula } 2$$

3. For alternative m with function coefficient of $F^m$ and cost coefficient of $C^m$, its value coefficient is $V^m$ as shown in formula 3

$$V^m = \frac{F^m}{C^m} \quad \cdots \textit{Formula } 3$$

4. After ranking the alternatives based on their value coefficient, the one with the highest value coefficient is selected as the optimal alternative. The model implementation process is as shown in Figure 3.

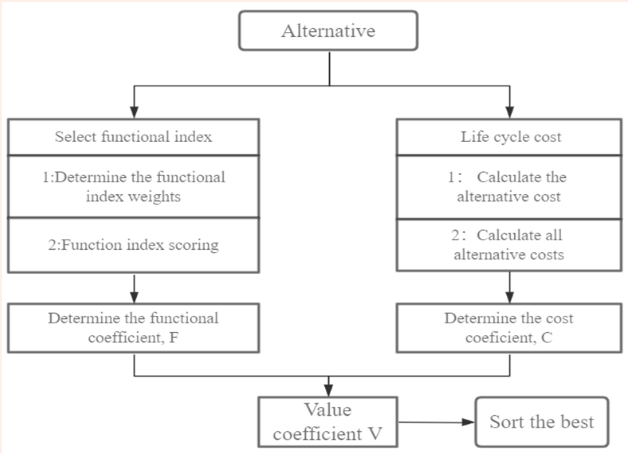


**Figure 3:** Algorithm flow of type selection of prefabricated building structural system.

# Case Study

## Information of the project

A planned building with 17 floors and total floor area of 3925㎡in an industrial zone in Changsha, China is selected as case study object. It has three alternative systems: traditional cast-in-situ structure, prefabricated frame cast-in-situ shear wall structure and externally hung and internally cast PCF shear wall structural system.

This case study assumes the following research premises:

a) The traditional cast-in-situ structure, fabricated frame cast-in-situ shear wall structure and “externally hung and internally cast” PCF shear wall structural system are built in the same geographical location.
b) Eliminate the influence of force majeure factors and artificial demolition and other factors.
c) According to the design service life of residential buildings, this paper takes the life cycle of the building as 60 years.
d) Consider inflation and bank interest rate and set the discount coefficient as 10%.

## Calculation of alternatives cost coefficient

### Basic information of the calculation

a) The cost of the alternative system (fees, taxes, safe and civilized construction costs, etc.) is mainly based on the consumption standard of Hunan housing construction and decoration projects in 2020 (base price version)
b) Price of main materials: the prefabricated components are calculated according to the main data provided by Hunan Provincial Housing Construction Standards; The traditional cast-in-place concrete structure is calculated according to the market price of Hunan Province, and the price of other materials is included according to the market price
c) Labor cost, machinery cost and other related costs shall be included according to the market price of Hunan Province;
d) The Chinese yuan is used as the unit of currency in this case study.

In summary, the unit prices and costs of the main components of the alternative system are summarized in Table 4 and Table 5

**Table 4:** Comparison of unit prices of main components of three alternative systems.

| Name | Unit | Unit price | | |
|---|---|---|---|---|
| | | Traditional cast-in-place structure | External hanging and internal pouring PCF shear wall structure | Fabricated frame cast-in-situ shear wall structure |
| exterior wall | $m^3$ | 646.597 | 2492.92 | 2610.62 |
| Interior wall | $m^3$ | 646.436 | 2303 | 2583.006 |
| column | $m^3$ | 628.78 | 2590.31 | 2590.31 |
| beam | $m^3$ | 642.647 | 2578.46 | 2578.46 |
| floor | $m^3$ | 646.92 | 2221.42 | 2221.42 |
| stairs | $m^3$ | 187.107 | 2433.1 | 2433.1 |

**Table 5:** Summary of costs of three alternative systems.

| Name | Total Price | | | Unit Price (yuan/square meter) | | |
|---|---|---|---|---|---|---|
| | Traditional cast-in-place | Externally hung and internally cast PCF shear wall | Fabricated frame cast-in-situ shear wall | Traditional cast-in-place | Externally hung and internally cast PCF shear wall | Fabricated frame cast-in-situ shear wall |
| Direct costs | 3971472.00 | 4393174.00 | 4703994.75 | 1011.84 | 1119.28 | 1198.47 |
| depreciation charge | | 140581.57 | 150527.83 | | 35.82 | 38.35 |
| profit | | 499503.88 | 534844.20 | | 127.26 | 136.27 |
| Safe and civilized construction cost | 177842.52 | 79516.45 | 85142.30 | 45.23 | 20.26 | 21.69 |
| Fees | 88087.25 | 39538.57 | 42335.95 | 22.44 | 10.07 | 10.79 |
| Taxes | 436861.92 | 483249.14 | 517439.42 | 111.30 | 123.12 | 131.83 |
| Input tax deduction | -281974.51 | -487642.31 | -522143.42 | -71.84 | -124.24 | -133.03 |
| Total | 4392289.18 | 5147921.3 | 5512141.03 | 1118.97 | 1311.57 | 1404.37 |
| difference | | | | | 192.60 | 285.40 |

### Cost coefficient of alternative structural system

a) **Production cost C1**

i. **Decision Making Cost ($C_{11}$)**

After consulting researchers in relevant industries, we know that the allocation of decision-making costs in the three alternative systems is the same, which has no impact on the estimation of their full life cycle costs. Therefore, we assume that the cost of this part is P yuan, that is, $C_{11}$=P yuan.

ii. **Design Cost ($C_{12}$)**

According to the consultation and data review, the design cost is calculated in yuan/㎡, and the prices for the three systems are 15 yuan/m$^2$, 19 yuan/ m$^2$ and 17 yuan/ m$^2$ respectively.

Thus, the total design cost for each alternative is as follows:

Traditional cast-in-situ $C_{12}$=15 × 3925=58900 yuan

Externally hung and internally cast PCF shear wall $C_{12}$=19 × 3925=74600 yuan

Fabricated frame cast-in-situ shear wall $C_{12}$=17 × 3925=66700 yuan

iii. **Construction and installation cost ($C_{13}$)**

After reviewing the industry's standard and market conditions, the construction and installation costs of three alternatives are as follows [35]:

Traditional cast-in-situ $C_{13}$=6,856,900 yuan

Externally hung and internally cast PCF shear wall $C_{13}$=8,609,400 yuan

Fabricated frame cast-in-situ shear wall $C_{13}$=8,973,600 yuan

iv. **Facility Cost ($C_{14}$)**

Under the same use conditions, the allocation of the facility cost of the building is the same disregard its structural system [36]. Therefore, it is assumed that the cost of this part is Q 10,000yuan, that is, $C_{14}$=Q 10,000yuan for all three alternatives.

Thus, by take the sum of four costs calculated above, the total production cost for each structural system is:

For the traditional cast-in-situ system, the construction and installation cost is $C_1=C_{11}+C_{12}+C_{13}+C_{14}$=P+5.89+685.69+Q=P+Q+6,915,800 yuan, its net present value is $NPV_1$=P+Q+6,915,800 yuan.

For the externally hung and internally cast PCF shear wall system, the construction and installation cost is:

C1=C11+C12+C13+C14=P+7.46+860.94+Q=P+Q+8,684,000 yuan, its net present value is $NPV_1$=P+Q+8,684,000 yuan

For the fabricated frame cast-in-situ shear wall system, the construction and installation cost is:

C1=C11+C12+C13+C14=P+6.67+897.36+Q=P+Q+9,040,300 yuan, its net present value is NPV1=P+Q+9,040,300 yuan

b) **Use-cost $C_2$**

i. **Property management cost($C_{21}$)**

In Changsha, the property management cost is priced according to the property management company's qualification level. The higher qualification level charges higher fees, which normally ranges from 0.5 to 4 yuan/month/m$^2$. This paper calculates the general charge of Changsha property as 1.8 yuan/month/square meter. Therefore, the property management cost C21=1.8 × 12 × 3925=84,800 yuan for all structural systems.

ii. **Energy consumption cost($C_{22}$)**

According to the market survey, the building energy consumption cost of the traditional cast-in-place structural system is 23.79 yuan/year/㎡. As the prefabricated structural system has better light bearing performance and thermal insulation performance, its energy consumption cost is smaller [37]. The energy consumption cost of the prefabricated structural system building is determined to be 15.89 yuan/year/square meter. So, the energy consumption cost for each structural system is:

Traditional cast-in-place $C_{22}$=23.79 × 3925=93400 yuan

Externally hung and internally cast PCF shear wall $C_{22}$=15.89 × 3925=62700 yuan

Fabricated frame cast-in-place shear wall $C_{22}$=15.89 × 3925=62700 yuan

iii. **Repair Cost ($C_{23}$)**

In the current industry practices, for traditional cast-in-situ buildings, major repair is needed every 15 years, that is, in its design service life, three major repairs need to be performed and the price for each repair is 150,000, 250,000 and 400,000 yuan. For prefabricated buildings, due to their higher quality, major repairs are only needed every 20 years [38] and the price for each repair is 200,000 and 400,000 yuan.

iv. **Maintenance Cost ($C_{24}$)**

According to current market specifications in Hunan province, the standard for the maintenance fee of traditional cast-in-place structural buildings is 101 yuan per square meter, and the standard for that of prefabricated buildings is 51.9 yuan per square meter. So, the maintenance fees for each structural system is:

Traditional cast-in-place $C_{24}$=101 × 3,925=396,400 yuan

Externally hung and internally cast PCF shear wall $C_{24}$=51.9 × 3,925=203,700 yuan

Fabricated frame cast-in-situ shear wall $C_{24}$=51.9 × 3,925=203,700 yuan

Therefore,

The net present value of the alternatives' use-costs is:

Traditional cast-in-place structure:

$NPV_2$=(8.48+9.34)×(P/A,10%,60)+15×(P/F,10%,15)+25×(P/F,10%,30)+40×(P/F,10%,45)+39.64×(P/F,10%,60)=177.61+3.59+1.43+0.55+0.13=1,833,100 yuan

Externally hung and internally cast PCF shear wall structure:

$NPV_2$=(8.48+6.27)×(P/A,10%,60)+20×(P/F,10%,20)+40×(P/F,10%,40)+20.37×(P/F,10%,60)=147.02+2.97+0.88+0.07=1,509,400 yuan

Fabricated frame cast-in-situ shear wall structure:

$NPV_2$=(8.48+6.27)×(P/A,10%,60)+20×(P/F,10%,20)+40×(P/F,10%,40)+20.37×(P/F,10%,60)=147.02+2.97+0.88+0.07=1,509,400 yuan

c) **Demolition and recovery cost $C_3$**

After the service life of the traditional cast-in-place structure is completed, its net residual value accounts for about 3% of the construction and installation cost, while after the service life of the prefabricated structural system is reached, its net residual value accounts for about 10% of the construction and installation cost [39] (Figure 4). So, the demolition and recovery cost and the present net value for each structural system is:

Traditional cast-in-place cost:

$C_3$=685.69 × 3%=205，700 yuan

Traditional cast-in-place NPV:

$NPV_3$=20.57×（P/F, 10%, 60 = 700 yuan

Externally hung and internally cast PCF shear wall:

$C_{24}$=51.9 × 3,925=203,700 yuan

Externally hung and internally cast PCF shear wall NPV:

$NPV_3$=86.09×(P/F,10%,60) = 2,800 yuan

Fabricated frame cast-in-situ shear wall:

$C_{24}$=51.9 × 3,925=203,700 yuan

Fabricated frame cast-in-situ shear wall NPV:

$NPV_3$=89.74×(P/F,10%,60) = 2,900 yuan

d) **NPV of the Life Cycle Cost of the alternative Structural systems**

Traditional cast-in-place:

NPV=$NPV_1$+$NPV_2$-$NPV_3$=P+Q+691.58+183.31-0.07=P+Q+8,748,200 yuan

Externally hung and internally cast PCF shear wall:

NPV=$NPV_1$+$NPV_2$-$NPV_3$=P+Q+868.40+150.94-0.28=P+Q+10,190,600 yuan

Fabricated frame cast-in-situ shear wall:

NPV=$NPV_1$+$NPV_2$-$NPV_3$=P+Q+904.03+150.94-0.29=P+Q+10,546,800 yuan

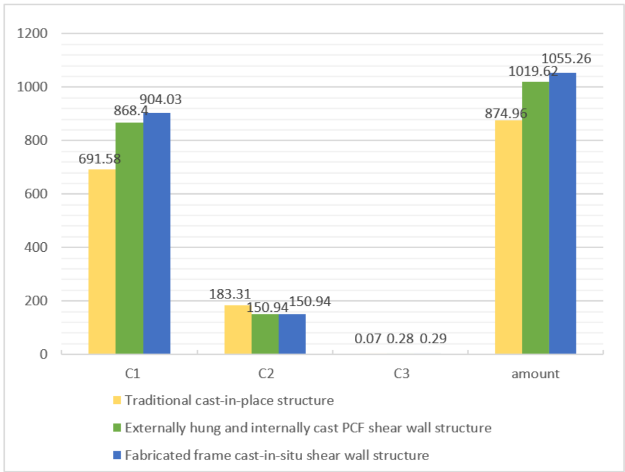


**Figure 4:** Life cycle comparison of alternative systems.

e) **Cost Coefficient of the Alternative Structural systems**

The cost coefficient of each alternative is as shown in Table 6.

**Table 6:** Cost coefficient of alternative structural system.

| Programme | Traditional cast-in-place structure | Externally hung and internally cast PCF shear wall structure | Fabricated frame cast-in-situ shear wall structure |
|---|---|---|---|
| Cost coefficient | 0.297 | 0.346 | 0.357 |

## Functional coefficient of each alternative structural system

For the cast-in-place structural system, the externally hung and internally cast PCF shear wall structural system, and the fabricated frame cast-in-place shear wall structural system, the expert scoring method of 10 points system is used to score the functions. As shown in Table 7, A1 refers to cast-in-situ structural system, A2 refers to externally hung and internally cast PCF shear wall structural system, and A3 refers to fabricated frame cast-in-situ shear wall structural system.

**Table 7:** Scoring alternative architecture

| | f11 | f12 | f13 | f14 | f21 | f22 | f23 | f24 | f31 | f32 | Weighted Score | Function coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.117 | 0.144 | 0.139 | 0.1 | 0.067 | 0.089 | 0.089 | 0.105 | 0.078 | 0.072 | | |
| A1 | 7 | 6 | 6 | 7 | 6 | 6 | 6 | 6 | 6 | 6 | 6.217 | 0.27 |
| A2 | 9 | 9 | 8 | 8 | 9 | 9 | 9 | 10 | 9 | 9 | 8.866 | 0.385 |
| A3 | 8 | 8 | 7 | 7 | 8 | 8 | 9 | 9 | 8 | 8 | 7.955 | 0.345 |
| total | | | | | | | | | | | 23.038 | 1 |

## Value coefficient of each alternative structural system

After a combined analysis of the life-cycle cost coefficient and functional coefficient of the three alternative structural systems, the value coefficient of each alternative can be calculated and the results are shown in Table 8.

**Table 8:** Value coefficient analysis of alternative structural system.

| Program | Function coefficient | Cost coefficient | Value coefficient |
|---|---|---|---|
| Traditional cast-in-place structure | 0.27 | 0.297 | 0.909 |
| Externally hung and internally cast PCF shear wall structure | 0.385 | 0.346 | 1.113 |
| Fabricated frame cast-in-situ shear wall structure | 0.345 | 0.357 | 0.966 |

The following conclusions can be drawn from the results:

The life cycle cost of the cast-in-place structural system has the lowest LCC, which seems to be the optimal option, however, its functional coefficient is the lowest among the alternative systems, so its value index is smaller than the other two alternative systems. The prefabricated frame cast-in-situ shear wall structural system has the highest life-cycle cost coefficient, but its functional coefficient is high, so its value coefficient is higher than that of the cast-in-situ structural system.

The functional coefficient of the externally hung and internally cast PCF shear wall structural system is the highest among the alternative systems, and its life-cycle cost coefficient is in the middle, so its value coefficient is highest. The comparative analysis of the three alternative systems shows that the externally hung and internally cast PCF shear wall structural system can achieve the maximum functional value with less cost. Therefore, through the value coefficient analysis, the external hanging and internal pouring PCF shear wall structural system should be selected in this case.

## Conclusion

This paper mainly analyzed five kinds of concrete prefabricated building structural systems, and established a model for the structural system selection based on value engineering. During the course of completing the research and from the results of the provided case study, the following conclusions are drawn:

a) Greater development of prefabricated buildings is inevitable, aside from developing new prefabrication techniques, it is also very important to diversify the approach being used to select suitable structural systems. The model proposed in this paper not only provides insight to the factors that can be considered in the structural system selection stage, but also gives attention to solving this problem from a life cycle perspective.

b) Different prefabricated structural systems alone with the traditional cast-in-place structure have significantly different function coefficients and cost coefficients. This further confirms the importance of using value coefficient as an indicator in the structural system selection stage because the preference of each stakeholder of a construction project often varies. For example, the investors always tend to minimize the financial cost while the architecture focuses on the aesthetic perspectives and the structural engineers mainly consider the construction feasibilities.

c) From the LCC analysis, it can be noticed that prefabricated buildings have higher cost than traditional buildings. This confirms the current market situation of prefabricated buildings and the main reason causing the high cost is that prefabricated buildings are still not fully industrialized, only limited companies and factories are able to provide professional detailed design and prefabricated components production services which makes the unit price of prefabricated buildings are higher than traditional buildings.

d) From the case study, it is found that the value coefficients of prefabricated building structures are higher than that of the traditional cast-in-place building. This indicates that despite the fact that prefabricated buildings have higher costs, they can achieve higher value through their life cycles, which give more indirect benefits in long term.

## Future Works

In the life-cycle cost analysis, various factors can affect the calculation results, and thus affect the decision-making in the structural system selection process. Therefore, if more data is available, the accuracy of the LCC estimations of all building types can be further improved. In addition, in real-world applications, the market factor, policy factor and other external factors that can have influence on the structural system selection results should also be considered.

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