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Sustainable Performance of Buildings through Modular Prefabrication in the Construction Phase: A Comparative Study

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Abstract: Prefabrication has been considered an effective alternative to conventional building. It has gained an increasing amount of attention over the last few decades as a way to advance sustainable construction. This study focused on the construction stage to compare sustainable performances of prefabrication with conventional building. Sixteen indicators were extracted from a literature review and specialist interviews to conduct a sustainability evaluation. A survey was delivered to developers, designers, superintendents, manufacturers, and contractors of a Chinese case project. A total of 51 valid responses were collected. Projection pursuit (PP), based on the real-coded accelerating genetic algorithm (RAGA), was employed to evaluate the sustainability of prefabrication. The results showed that there was a consensus among the participants that prefabrication has more obvious sustainable performances in the construction phase compared with conventional building. However, cognitive differences among the participants regarding the sustainability of prefabrication were also pronounced. The findings presented in this paper may assist the government to propose feasible policies and measures to promote the development of prefabrication in China.

Keywords: prefabricated residential building; sustainable performances; construction phase; participants

1. Introduction

Buildings have long been criticized not only for their low productivity, long construction time, and poor quality and safety [1] but also for their energy consumption and environment pollution [2,3]. According to the International Energy Agency, the building industry is one of the largest contributors to energy consumption and CO_2 emissions [4]. Buildings consume more than 50% of steel production, 60%–70% of cement production, 50% of urban construction land, and 40%–50% of overall energy consumption in their life cycle [5]. The consumption is greater in developing countries owing to the low durability and poor quality of construction, as well as the high amount of waste of resources and energy. For example, building construction consumes 30% more water, 10%–25% more steel, and 80 kg of cement per cubic meter of concrete in residential buildings compared with that in developed countries [6]. Therefore, green buildings with sustainable construction approaches have become a necessity and can be realized through innovations and advances in building technology [7].

In recent years, buildings utilizing advanced modular prefabrication have gained more attention in the architectural, engineering, and construction (AEC) industry. These new buildings are considered as a novel solution to tackle the shortcomings of conventional buildings [8,9]. Modular prefabrication refers to a new construction approach where building components are manufactured in a controlled environment, transported, positioned, and assembled at the construction site [10]. This approach is also known as off-site construction [11], industrialized building (IB) construction [12,13], and modular building construction [14].

Modular prefabrication helps improve sustainability in construction and provides environmental benefits [15,16]. However, most studies have focused on the life cycle building performance as a whole, and few have shed light on the particular sustainable performance in specific phases, such as design, construction, operation, and maintenance. The main stakeholders involved in various phases are different and their concerns, interests, and decision-making vary. In the current highly fragmented construction industry, sustainable performance in response to stakeholders' concerns affects their decisions and active participation in selecting modular prefabrication [17]. As shown by Morris and Hough, insufficiently addressing the stakeholders' concerns may lead to project failure [18]. In a building's life cycle, the construction phase is critical because (1) many stakeholders are involved, such as developers, designers, superintendents, manufacturers, and contractors [19]; (2) it is particularly important for optimizing the energy use of a building's life cycle [20]; and (3) the environmental means in this phase has a great impact [21].

Therefore, the objective of this study was to identify the sustainable performance of the modular prefabrication approach in the construction phase. We compared performances between buildings that were built using modular prefabrication and conventional construction approaches. The comparison was developed based on a real-world residential construction case. The case project consisted of two parts: part A was a prefabricated residential building and part B was a conventional residential building. It should be noted that the difference between parts A and B was only the construction approach, whether modular prefabrication or not. Our results provide quantifiable evidence to the key stakeholders in construction, especially the contractors, to evaluate modular prefabrication.

2. Background

In the last decade, the sustainable benefits of modular prefabrication compared to conventional building construction have attracted the attention and interest of researchers. Many studies have evaluated the comprehensive sustainable benefits of prefabrication. For example, Tam et al. identified the advantages of using prefabrication in enhancing the quality of prefabricated products, shortening construction time, reducing construction costs, and improving environmental performance and aesthetics [22]. Jaillon and Poon concluded that there are sustainable benefits to adopting prefabrication in terms of quality and safety, construction time, labor demand, and environmental performance [2]. Boyd et al. pointed out the advantages of off-site construction regarding construction time, building quality, and occupational health and safety [23]. Blismas et al. demonstrated the on-site benefits of prefabrication, including minimizing on-site operations, duration, and labor; reducing congested work areas and multitrade interfaces; and improving health and safety [24]. Boafo et al. pointed out that prefabrication improved the speed of construction, quality of architecture, efficiency of materials, and worker safety and limited the environmental impacts of construction [25]. Jiang et al. found that IB efficiency has a positive effect on the economic factors, livability, safety, environmental factors, and social benefits [26]. Environmental performance evaluations are also of great interest to many researchers. For example, Pons concluded that prefabricated buildings are more sustainable than non-prefabricated buildings for consuming less energy and water and producing fewer emissions [27]. Cao et al. demonstrated that prefabrication has a clear advantage in material consumption, energy use, and water discharge [28]. In addition, many studies have focused only on one or a very limited number of indicators to discuss the benefit of prefabricated building, for example, waste generation [29,30] and incremental costs or cost savings [31,32]. Tam and Hao pointed out that construction waste was greatly reduced in various on-site activities [30]. Mao et al. found that the cost savings of prefabrication were due to labor reduction and less delivery time [31].

Modular prefabrication, which offers opportunities to develop sustainable construction, has been widely used and improved in some developed countries and regions, such as the United States, the

Europe Union, the United Kingdom, Japan, and Singapore [10,33,34]. In China, prefabrication has increasingly gained the attention of the government. For example, it was put forward in the document "The Opinions of the Central Committee of the Communist Party of China and State Council on Further Strengthening the Administration of City Planning and Construction" in 2016 to vigorously develop prefabricated buildings so as to shorten construction time, reduce construction waste and dust pollution, and improve construction quality. As noted in this document, the proportion of prefabricated buildings would account for 30% on new buildings in 10 years by increasing policy support. In recent years, prefabricated technologies have improved in China. By the end of 2017, the Ministry of Housing and Urban–Rural Development of the People's Republic of China (MOHURD) had authorized 30 pilot cities and 195 enterprises as industry bases for promoting the development of prefabricated building. However, China's application of the prefabricated building still lags behind [35]. The share of prefabricated buildings in China is below 2% of the whole building industry [36]. The initial high incremental cost is a critical barrier to the application of prefabrication. Another issue is that the sustainable benefits of prefabricated buildings, compared with conventional buildings, are not fully understood by different practitioners and the public [37].

The sustainable benefits of prefabricated buildings have been addressed in many studies. However, only a few have focused on the comprehensive benefits of prefabricated buildings in the construction phase. Mao et al. pointed out that prefabricated buildings result in fewer emissions than conventional buildings in the construction phase [11]. Tam et al. found that there are cost savings from material and site manpower reductions in the construction phase of public and private prefabricated residential buildings [38]. In addition, the projects selected to compare sustainable performance between prefabricated and conventional buildings have been different in some case studies. For example, Mao et al. compared sustainable performances in a prefabricated public rental housing project and a conventional general residential project [11]. The benefits of prefabricated buildings are largely dependent on project-specific conditions [24,27]. So, it is fundamental to choose similar projects, with the only difference being the building technology (prefabricated or conventional), to compare their sustainable performances.

3. Data and Methods

The process of this study is shown in Figure 1. First, the sustainable indicators were extracted from a comprehensive literature review and specialist interviews. Then, data collection was conducted from two real-world construction projects. The sustainable performance in the construction phase was compared between modular prefabrication and non-prefabrication projects using the projection pursuit (PP) model. The model is based on the real-coded accelerating genetic algorithm (RAGA) and shows good performance in reducing dimensions for high-dimensional data. Finally, the implications are discussed based on the evaluation results.

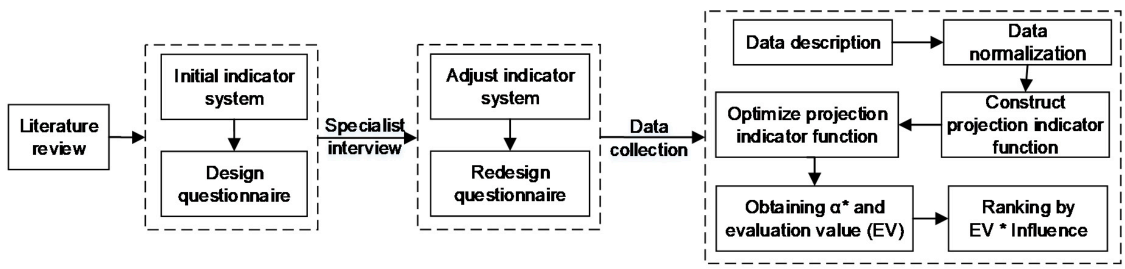

Figure 1. Study process.

3.1. Data

The case project is a residential project located in Shandong Province, China (Figure 2). The project consists of two parts: part A contains six buildings and uses the modular prefabrication approach; part

B contains three buildings and uses the conventional construction approach. It is noteworthy that the two parts have exactly same building design, including orientation, architectural layout, structural materials, and mechanical systems. The case project provides great industrial data to validate the sustainability performance due to the varying construction approaches. The total construction area of part A is about 93,443 m^2, in which 3–18 layers adopt an assembled integral shear wall structure, and the joints between the components adopt the method of second casting on site. Prefabricated components are utilized, including prefabricated prestressed composite slab, prefabricated sandwich insulation wallboard, prefabricated shear wallboard, integral light wallboard, and prefabricated staircases. The prefabrication rate can reach 75%. The total construction area of part B is about 36,900 m^2, in which a cast-in-place concrete shear wall structure is used.

Figure 2. The case project.

We conducted a survey on the case project stakeholders, who fully understand the construction process in both parts A and B. They are the experts and observers who have gained knowledge and experience regarding the differences between modular prefabrication and conventional construction. The respondents consisted of developers, designers, superintendents, prefabrication manufacturers, and contractors. The survey was sent to the construction site, the prefabrication plant, and the design unit. In total, 51 questionnaires were issued and 51 were returned, thus resulting in a response rate of 100%. In the survey, the respondents were requested to assign an appropriate rating on the difference between the two construction approaches using a 5-point Likert scale ranging from 1 to 5. Point 1 means the change is "the least significant", or an indicator is minor or nonexistent. Point 5 means the change is "the most significant", or an indicator is extremely apparent in prefabricated buildings. Among the 51 responses, 8 were from developers, 9 from designers, 7 from superintendents, 11 from manufacturers, and 16 from contractors, as shown in Table 1.

3.2. Measurement

Table 2 shows the indicator system that we created to measure the sustainable performance of buildings that was tailored for the construction phase. The survey distribution and responses are shown in Table 1. The system was built upon a literature review and specialist interviews; in particular, it was based on the work of Kamali and Hewage, who developed the most commonly used indicator system for assessing building sustainability [39]. We also interviewed eight project experts regarding pilot indicators that are relevant to construction activities in the construction phase, including three academics, one developer, one designer, one supervisor, one manufacturer, and one contractor. All of these experts have more than six years of experience in researching and practicing of modular prefabrication. The interviews were completed at a face-to-face conference. Finally, 16 indicators were selected for the indicator system: five indicators belong to the economic dimension, including cost savings, construction time, labor reduction, executing costs, and weather disruption; six indicators belong to the environmental dimension, including site disruption, construction waste, pollution generation, energy consumption, water consumption, and formwork consumption; and five indicators belong to the social dimension, including constructability, health and safety risk, construction quality, aesthetic options, and labor availability.

Table 1. Survey distribution and responses.

Respondents	Number of Responses		Percentage (%)
	Sent-Out	Valid Responses	
Developers	8	8	15.69%
Designers	9	9	17.65%
Superintendents	7	7	13.73%
Manufacturers	11	11	21.57%
Contractors	16	16	31.37%

Table 2. Indicator system of sustainability.

Dimension	Indicator	Brief Descriptions	Reference
Economic	Cost savings	The reduction of costs including labor, materials, and machinery equipment fees.	[1–3,15,23,26,27,39,40]
	Construction time	Total duration of construction from planning to project delivery.	[1,2,15,16,22,23,27,39–41]
	Labor reduction	The amount of labors used on site	[1–3,15,39,41–43]
	Executing costs	The costs of construction activities' execution and operation on site.	[16,43]
	Weather disruption	Total duration of schedule delays due to adverse weather.	[1,15,39,42]
Environmental	Site disruption	Construction activities influenced by labor, materials, machineries equipment, and environment on site	[1,2,15,39,40,42]
	Construction waste	The amount of construction waste produced on site	[1,2,15,22,27,34,39,44,45]
	Pollution generation	Pollution level on site (e.g., noise, dust, etc.)	[1,2,15,26,39,44,45]
	Energy consumption	The amount of diesel and electricity used during the construction phase	[1,3,15,26,27,39,43–45]
	Water consumption	The amount of water used on site.	[1,3,15,27,39,44,45]
	Formwork consumption	The amount of formwork used on site.	[1–3,15,26,39,45]
Social	Constructability	The difficulty degree of construction	[1,2,15,16,41]
	Health and safety risk	Risks of health and safety issues in the workplace (e.g., injury, fatality, etc.).	[1,2,15,16,23,26,27,39,41,42]
	Construction quality	The quality and durability of building (e.g., fewer de-bonding tiles and water leakage).	[15,23,40,42,46]
	Aesthetic options	Visual appearance of internal and external of the building.	[1,2,15,16,22,41,45]
	Labor availability	The amount of available labor to need.	[1,15,39]

3.3. Data Analytics

We used the PP mathematical method for multivariate data analysis that projects high-dimensional data into a low-dimensional subspace. PP is an advanced computing technique that reflects the structure or characteristics of the original high-dimensional data based on the projection eigenvalue [47]. PP has been used in many fields, such as energy [48,49], environmental studies [50,51], agriculture [52,53], and medicine [54], to comprehensively evaluate and determine major influencing factors. We chose PP rather than factor analysis because it offers a strong advantage for the comprehensive evaluation of high-dimensional, non-normal, and non-linear complex problems [48]. Hou and Wentzell pointed out that PP outperforms principal component analysis in exploratory data analysis because PP can reveal "interesting" data structures by project directions [52]. We utilized MATLAB 2017 software to perform the PP analysis.

The PP procedure includes four major steps:

Step 1. Normalization of sample sets.

Assume the sample set is $\left\{x^*_{ij}\middle|i = 1, 2, \cdots, n, j = 1, 2, \cdots, p\right\}$. x^*_{ij} represents the jth indicator value in the ith sample set, and n and p represent the number of samples and indicators, respectively. The normalization process can be performed using Equations (1) and (2).

Equation (1) is for the bigger and better indicators:

$$x_{ij} = \frac{x^*_{ij} - x_{j-\min}}{x_{j-\max} - x_{j-\min}} \tag{1}$$

where $x_{j-\min}$ and $x_{j-\max}$ represent the maximum and minimum values of the jth indicator, respectively.

Equation (2) is for the smaller and better indicators:

$$x_{ij} = \frac{x_{j-\max} - x^*_{ij}}{x_{j-\max} - x_{j-\min}}. \tag{2}$$

Step 2. Construct projection indicator function.

The PP actually converts the p-dimensional data $\{x_{ij}\big|j = 1, 2, \cdots, p\}$ into the one-dimensional projection value z_i, with $\alpha = \{\alpha_1, \alpha_2, \alpha_3, \cdots, \alpha_p\big\}$ as the projection direction, in which α is the unit length vector. First, it is represented as follows:

$$z_i = \sum_{j=1}^{p} \alpha_j x_{ij} \times (j = 1, 2, \ldots, n) \tag{3}$$

Then, it is classified according to a one-dimensional scatter plot of the projected values. The projection points should be spread as much as possible on the whole. Then, the projection indicator function can be expressed as follows:

$$Q_\alpha = S_z D_z \tag{4}$$

where S_z and D_z represent the standard deviation and local density of z_i, respectively, which are shown in Equations (5) and (6):

$$S_z = \sqrt{\frac{\sum\limits_{i=1}^{n} (z_i - E_Z)^2}{n-1}} \tag{5}$$

$$D_z = \sum_{i=1}^{n} \sum_{j=1}^{n} (R - rij) \cdot u(R - rij) \tag{6}$$

where E_z is the average valve of z_i, and R is the density window radius of D_z. r_{ij} is the distance between the samples, and u_t represents the unit step function as follows:

$$u_t = \begin{cases} 1 & t > 0; \\ 0 & otherwise \end{cases} \tag{7}$$

Step 3. Optimize projection indicator function.

The optimal projection direction reflects the most likely feature structure for the high-dimensional data, which is obtained by maximizing the projection index function as follows:

$$\begin{cases} \max : Q_a = S_z \cdot D_z \\ s.t. : \sum\limits_{j=1}^{p} \alpha_j^2 = 1 \end{cases} \tag{8}$$

RAGA was used to solve the high-dimensional global optimization problem. RAGA is an adaptive global optimization probability search algorithm that is based on overcoming the shortcomings of binary coding used by standard genetic algorithms [55,56]. The optimization problem is as follows:

$$\begin{cases} Max : f(x) \\ s.t. : a_j \le x_j \le b_j \end{cases} \tag{9}$$

(1) Generating random variables. Generate N sets of uniformly distributed random variables $V_i^0\left(x_1, x_2, \cdots, x_j, \cdots, x_p\right)$, $i = 1, 2, \cdots, N, j = 1, 2, \cdots, p$, in the interval of change $[a_j, b_j]$ of each variable. N is the population size, p is the number of optimized variables, and V_i^0 represents the paternal chromosome.

(2) Calculating the objective function value. Substitute V_i^0 into the objective function to find the corresponding function value $f^0\left(V_i^0\right)$ and reorder the chromosomes according to the size of the function value, denoted as V_i^1.

(3) Calculation of order-based evaluation function by Equation (10):

$$eval(V_i) = \alpha(1-\alpha)^{i-1}, i = 1, 2, \cdots, N, \alpha \in (0, 1). \tag{10}$$

(4) Selecting the first offspring population. The chromosome is selected for each new population by roulette selection, and a new population is obtained after the selection operation.

(5) Cross-operation to produce the second offspring population. We defined the parameter P_c as the crossover probability and assumed the sequence $V_1', V_2', \cdots$ as the paternal population, so as to divide them into the following groups randomly: $\left(V_1', V_2'\right), \left(V_3', V_4'\right), \left(V_5', V_6'\right)$. Then, we could get a new population V_i^3 by using cross-operation for them in the following form:

$$X = cV_1' + (1-c)V_2', Y = (1-c)V_1' + cV_2', c \in (0, 1). \tag{11}$$

(6) Mutation operation to produce the third offspring population. Similarly, we defined parameter P_m as the probability of mutation ($P_m = 0.8$ following suggestions by Pandey et al. [57]), assumed the sequence $V = (x_1, x_2, \cdots, x_n)$ as the paternal population, and performed the mutation operation. The mutation direction d is randomly selected from R^n. If the value $V + Md$ (M is a sufficiently large number) is not feasible, then M is a random number between 0 and M until feasible. The value of M is zero. If there is no feasible solution in the given number of iterations, then it can replace V with $V + Md$ regardless of the value of M. We recorded the new population as V_i^4.

(7) Iterative evolution process. According to the fitness function value of V_i^4, it sorts from large to small. After this, return to step 3 to start a new round of the optimization process, and it must be re-evaluated, selected, crossed over, and mutated for the parent population until the end.

(8) Accelerated circulation. The above steps constitute a standard genetic algorithm (SGA). However, studies have shown that SGA does not guarantee global convergence, which may result in many individuals being similar or even repeating. The variable interval of the individual generated by the first, second, third, and fourth iterations is used as the new initial variation interval of the variable and then proceeds to (1). By accelerating the cycle, the optimal individual interval is gradually reduced and comes closer to the optimal distance. When the value of the optimal individual's optimization criterion function is less than the set value or the algorithm runs for a predetermined number of times (maximum = 30 in this study), then the algorithm ends.

Step 4. Comprehensive evaluation analysis.

According to the optimal projection direction, the projection eigenvalue z_i reflecting the comprehensive information of each evaluation index can be calculated, of which the sample group can be comprehensively analyzed with the difference level.

4. Results and Discussion

4.1. Difference of Sustainable Performance

The descriptive statistics of each indicator are shown in Table 3. According to the average value of each indicator (5 = "better performance of modular prefabrication", 1 = "better performance of traditional construction"), the results show three indicators that change significantly for modular prefabrication compared with conventional construction: formwork consumption (4.12), construction waste (4.08), and pollution generation (4.02). Ten indicators indicated moderate change: weather disruption (3.88), site disruption (3.84), labor reduction (3.73), executing costs (3.69), health and safety risk (3.63), water consumption (3.59), aesthetic options (3.53), construction quality (3.31), constructability (3.18), and construction time (3.12). Three indicators indicated little change: energy consumption (2.78), labor availability (2.57), and cost savings (2.12). We interpret the benefits of modular prefabrication as mostly relating to material usage in the environmental dimension. Surprisingly, the economic and social benefits, such as cost, labor, and energy, are not significant.

Table 3. Descriptive statistics of sustainable indicators.

Dimension	Indicators	Mean	Std. Dev.	Min.	Max.
Economic	Cost savings	2.1176	0.8160	1	3
	Construction time	3.1176	1.2907	1	5
	Labor reduction	3.7255	1.0969	1	5
	Executing costs	3.6863	0.8830	2	5
	Weather disruption	3.8824	0.8160	2	5
Environmental	Site disruption	3.8431	0.9874	2	5
	Construction waste	4.0784	0.8682	2	5
	Pollution generation	4.0196	0.8122	2	5
	Energy consumption	2.7843	1.1716	1	5
	Water consumption	3.5882	0.8984	2	5
	Formwork consumption	4.1176	0.8865	2	5
Social	Constructability	3.1765	1.2760	1	5
	Health and safety risk	3.6275	0.9372	2	5
	Construction quality	3.3137	1.1044	1	5
	Aesthetic options	3.5294	1.0070	2	5
	Labor availability	2.5686	1.0248	1	5

The results show higher sustainable performances on the indicators of formwork consumption (4.12), construction waste (4.08), pollution generation (4.02), weather disruption (3.89), and site disruption (3.83). First, these on-site improvements from adopting prefabrication are easily observed by comparing the prefabricated and conventional residential buildings in the case project. Second, the components manufactured in factories (such as exterior walls, interior walls, beams, plates, and exterior wall thermal insulation), which reduce greatly prefabricated activities on site [58], are an effective technology to improve environmental performance [28]. In our results, four out of five indicators with higher evaluation values are environmental indicators, indicating that prefabrication significantly contributes to the environmental improvement of the building industry. According to the data from the case project, a prefabricated residential building can save 60% of steel, 56% of concrete, and 77% of formwork on site.

Three indicators have much lower sustainable performances, including labor availability, energy consumption, and especially, cost savings, which is consistent with the current development situation for prefabricated buildings [59]. We calculated the consumption of the steel, concrete, and formwork used on site, and compared the difference. The difference confirmed that the cost per square meter is higher by 21% for prefabricated residential buildings compared with conventional residential buildings. The main reason for the increased cost is that the price of prefabricated components is relatively high. Presently, prefabricated residential buildings are only in the demonstration stage in China, and components manufacturers have been in an unsaturated production status for a long time, resulting in a higher one-time investment in the price of prefabricated components. So, prefabricated components were responsible for the high initial cost [31,33].

Traditional low-skill workers have been replaced by skilled workers in prefabrication; however, traditional workers are still employed in China, including for factory-produced components. Chang et al. also pointed out that the lack of skilled workers is one barrier to prefabricated buildings in China and that this is difficult to overcome in a short amount of time [60]. Labor instability is presently one of the main characteristics of the construction industry in China.

The evaluation of energy consumption was different than the extant research, which demonstrated there is an obvious energy savings benefit from adopting modular prefabrication [32,61]. According to the case project, electricity and diesel oil consumption in prefabricated residential building construction is higher by 27% and 41% compared with conventional construction, respectively, because electricity consumption increases greatly due to scaffolding and vertical transportation and diesel oil consumption increases greatly due to the trucking required to install protective steel grids and the truck cranes needed to unload prefabricated components.

The results also show that the construction time is slightly short (M = 3.12, SD = 1.29) when adopting prefabrication, indicating that construction time is not an obvious advantage compared with conventional construction. The case project located in the north of China, where the temperature is lower than minus 5 degrees Celsius from December to February, is not suitable for on-site assembly because the grouting material requires ambient temperatures over minus 5 degrees Celsius; otherwise, it would affect the stability of the structure.

4.2. Impact of Sustainable Performance

Table 4 demonstrates the overall evaluation results from the use of RAGA-based PP model.

The results show higher evaluation values in formwork consumption (5.76), construction waste (5.66), pollution generation (5.62), weather disruption (5.32), and site disruption (5.30) and lower evaluation values in cost savings (0.89), labor availability (2.03), and energy consumption (2.74). In general, the sum of squares of the best projection direction $(\alpha\ ^*)^2$ is often used as indicators' weights to reflect the impact of each indicator on sustainability [57]. As shown in Table 4, nine indicators were shown to have a greater impact on the sustainability of prefabrication, which accounted for 71.4% of the total. These indicators are aesthetic options (12.38%), construction waste (9.95%), construction quality (8.63%), site disruption (7.97%), water consumption (7.85%), pollution generation (6.48%), execution costs (6.26%), constructability (6.18%), and energy consumption (5.67%). Furthermore, we can see that some indicators have a big difference but also big impact. We calculated the (evaluation value (EV) * Influence) to show the performance of the indicators when adopting prefabrication (as shown in Figure 3). The results show that the indicators have greater performances for sustainable construction, such as aesthetic options (0.58), construction waste (0.56), site disruption (0.42), water consumption (0.36), and pollution generation (0.36), some of which have become hot research topics in recent years.

Table 4. The overall evaluation of all indicators.

Indicator	Evaluation Value (EV)	α *	$(\alpha *)^2$	Influence (%)	EV * Influence	Rank
Aesthetic options	4.6744	0.3519	0.1238	12.38%	0.5787	1
Construction waste	5.6611	0.3155	0.0995	9.95%	0.5633	2
Site disruption	5.3012	0.2823	0.0797	7.97%	0.4225	3
Water consumption	4.642	0.2802	0.0785	7.85%	0.3644	4
Pollution generation	5.6181	0.2545	0.0648	6.48%	0.3641	5
Construction quality	3.7638	0.2938	0.0863	8.63%	0.3248	6
Executing costs	4.6748	0.2501	0.0626	6.26%	0.2926	7
Labor reduction	4.6736	0.2225	0.0495	4.95%	0.2313	8
Constructability	3.7105	0.2485	0.0618	6.18%	0.2293	9
Health and safety risk	4.6737	0.2196	0.0482	4.82%	0.2253	10
Weather disruption	5.3201	0.1976	0.039	3.90%	0.2075	11
Formwork consumption	5.7626	0.1807	0.0327	3.27%	0.1884	12
Energy consumption	2.7400	0.2382	0.0567	5.67%	0.1554	13
Construction time	3.1795	0.1962	0.0385	3.85%	0.1224	14
Labor availability	2.0344	0.1809	0.0327	3.27%	0.0665	15
Cost savings	0.8872	0.214	0.0458	4.58%	0.0406	16

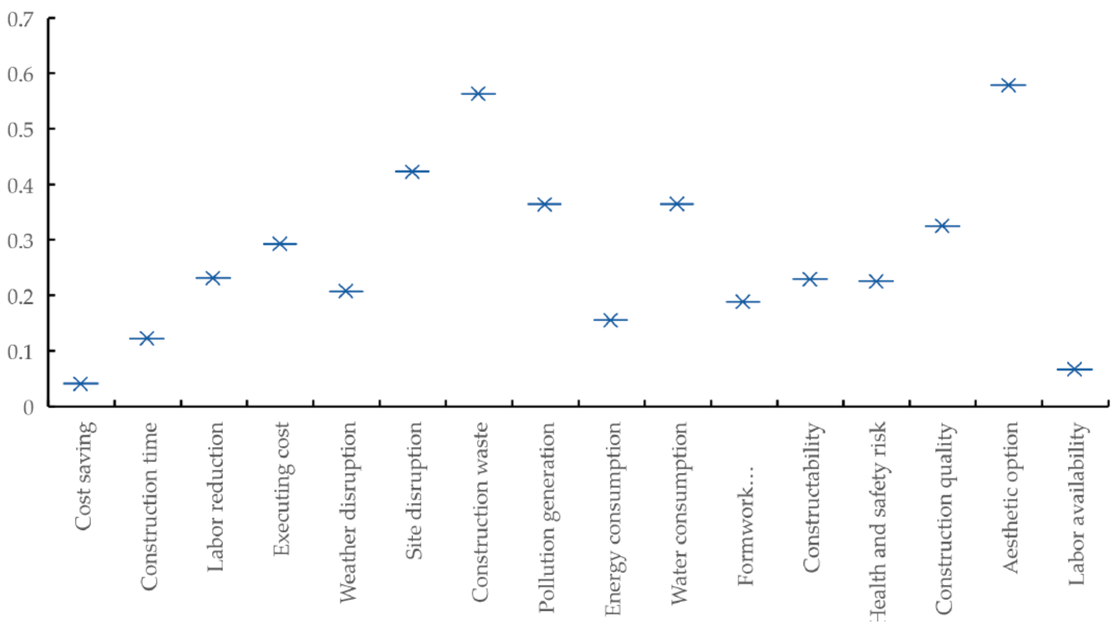

Figure 3. The performance of each indicator for sustainable construction.

4.3. *Cognitive Differences among Participants*

This study simultaneously optimized 16 parameters to compare the sustainability differences of participants' perceptions regarding prefabricated and conventional residential building construction (as shown in Table 5). Table 5 exhibits the results of analysis of variance (ANOVA). The results indicate that the differences among the participants were significant at the 5% level.

Table 5. The evaluation values of all respondents.

Respondents	Developers	Designers	Superintendents	Manufacturers	Contractors
Evaluation values	1.6575	0.9856	1.8649	1.3825	2.9504
	1.3892	1.1378	2.9407	2.0386	3.688
	1.3855	1.1367	1.8312	2.7740	2.4271
	2.3025	1.1149	2.5777	2.9161	3.2071
	2.7555	1.8249	1.7131	3.1627	3.0507
	1.1497	2.9504	2.7176	1.6579	2.9488
	2.1362	0.8019	3.0630	2.4643	2.7782
	3.5352	3.6670		2.9536	2.9394
		1.1031		2.9656	1.7070
				2.4167	1.7011
				3.3729	1.5756
					3.0628
					1.7872
					1.8092
					2.3708
					2.2179
Mean	2.0389	1.6358	2.3869	2.5550	2.5138
Std. Dev.	0.8121	1.0037	0.5693	0.6338	0.6538
C.V.	0.3983	0.6136	0.2385	0.2481	0.2601
	Sum of Squares	df	Mean square	F	Sig.
Between groups	5.986	4	1.496	2.748	0.039 **
Within groups	25.051	46	0.545		
Total	31.036	50			

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

The results show that the evaluation of manufacturers was highest regarding the sustainability of prefabricated building construction among all participants because manufacturers have been pushing for the development of prefabricated buildings, have been the earliest high-tech enterprises engaged in research, product development, manufacturing, and construction of prefabricated buildings in China, and have been awarded titles such as "National Housing Industrialization Base" and "Modern Production Base of the Construction Industry". The evaluations of superintendents and contractors were basically consistent with manufacturers, as they have full confidence in the development of prefabrication because local governments have been devoted to promoting prefabricated buildings in some new projects, such as public rental housing, renovations, resettlement housing in shanty towns, and government investment projects. However, the evaluation of developers and designers were quite different than the three aforementioned stakeholders, especially designers, whose evaluation was the lowest of all the participants because they have to accept passively government regulations advancing prefabrication with no "buffer period". For example, local governments are expected to give priority to supporting the development of prefabricated buildings in the arrangement of construction land. Moreover, relevant requirements for prefabricated buildings are included in the opinions on the planning and construction conditions of construction land and are implemented in land use contracts (People's Government of Shandong Province, 2017). In this study, we utilized the coefficients of variation (C.V.) to estimate the cognitive bias of different stakeholders. The results showed that the greatest cognitive bias exists among designers, followed by developers, contractors, manufacturers, and superintendents.

5. Conclusions

We conducted a survey study to evaluate the sustainable performances of prefabrication construction compared with conventional construction. Unlike the extant research, which has mainly focused on the life cycle of a building, we assessed sustainable performances in the construction phase based on the sustainable triple bottom line: economic, environmental, and social indicators. Our data were from a case project that was sponsored by the local government, which consists of two parts: part A is a prefabricated residential building and part B is a conventional residential building. In particular, it should be noted that the only difference between parts A and B is the building technology, that is, prefabricated or conventional. The major contribution of this study is that we extracted 16 sustainable indicators of the construction phase, consisting of 5 economic indicators, 6 environmental indicators, and 5 social indicators. The indicators were derived from a literature review and specialist interviews. To evaluate the sustainability of prefabrication and to identify the important indicators, the survey was conducted using participants from the case project, including developers, designers, superintendents, manufacturers, and contractors, and an evaluation of sustainability was carried out using PP based on RAGA by reducing dimensions.

Our results showed that a total of five indicators were evaluated at a higher value, including formwork consumption, construction waste, pollution generation, weather disruption, and site disruption. Among these indicators with higher evaluation values, environmental indicators made up a large percentage, which also demonstrates that prefabrication makes a significant contribution to the environmental improvement of the building industry. This conclusion is supported by the measured data of the case project, which showed that prefabrication can save 60% of steel, 56% of concrete, and 77% of formwork on site. Due to prefabrication being in the early stage of development in China [31], three indicators were evaluated much lower, including cost savings, labor availability, and energy consumption.

We found that participants' perceptions of the sustainability of prefabrication were different. The manufacturers gave the highest evaluation of the sustainability of prefabrication among all participants, followed by superintendents, contractors, developers, and designers. The evaluations of superintendents and contractors were basically consistent with the manufacturers. However, the evaluations of developers and designers were quite different from the manufacturers' evaluations. Furthermore, there was a difference in terms of bias among the same participants regarding the sustainability of prefabrication. The greatest bias was among designers, followed by contractors, developers, manufacturers, and superintendents.

This research confirms that modular prefabrication has many sustainable benefits over conventional approaches in the construction phase and has greater performances regarding sustainable construction in terms of construction waste, aesthetic options, site disruption, water consumption, and pollution generation. Also, there are differences in participants' perceptions of prefabricated residential buildings. So, at the present stage, the government should play an important role in promoting the development of prefabricated building construction, such as by strengthening propaganda and guidance to raise participants' awareness and understanding of the benefits of prefabricated buildings, establishing an incentive mechanism to stimulate participation in prefabrication, and pushing information sharing within the industry to better reveal the benefits of prefabrication. In addition, a limitation exists that data used in this study were from a massive project and the scalability needs further investigation in the future research.

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