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Barriers to Promoting Prefabricated Construction in China: A Cost–Benefit Analysis

Abstract: Prefabricated construction has attracted worldwide concern because of its significant role in the creation of sustainable urbanization. In Mainland China, the practice of applying prefabrication technology in the construction industry still lags behind. In fact, the economic benefit is a key concern of various stakeholders involved in the construction process and is expected to influence the delivery of prefabricated buildings significantly. Therefore, this study established a cost–benefit analysis framework to explore the basic cost composition of prefabrication and examined the effect of adopting prefabrication on the total cost of real building projects. Results show that the concrete and steel used in the typical prefabricated components were responsible for 26% to 60% of the total cost, followed by labor cost (17% to 30%) and transportation (10%). The average incremental cost is highly linearly correlated with the prefabrication rate, which ranged from 237 yuan/m^2 to 437 yuan/m^2, in eight building projects. To fully gain the economic benefits from the precast construction, the future focus should lie in providing financial support for promoting the development of prefabrication technology, optimizing the structure integrity of prefabricated buildings, and improving the maturity of the precast market.

Keywords: prefabricated construction, prefabricated component, cost–benefit analysis framework, case study

1. Introduction

Prefabricated construction refers to the practice of producing construction components in a manufacturing factory, transporting complete components or semi-components to construction sites, and finally assembling the components to create buildings (Tam et al., 2007). Other terms and acronyms that are associated with prefabricated construction include offsite construction (Pan et al., 2012), offsite prefabrication (Gibb, 1999), precast concrete building (Kale and Arditi, 2006), modern methods of construction, and industrialized building (Meiling et al., 2013). Precast products have been recently widely used in the building sector because of its advantages in environmental protection, quality and safety control, and construction scheme optimization (Chiang et al., 2006; Tam et al., 2015). Prefabricated construction can generally be categorized into the following four levels based on the degree of prefabrication implemented on the product: (1) component manufacturing and subassembly that are always done in a factory and not considered for onsite production, (2) non-volumetric pre-assembly that refers to pre-assembled units not enclosing usable space, such as timber roof trusses, (3) volumetric pre-assembly that refers to pre-assembled units enclosing usable space and usually being manufactured inside factories but do not form a part of the building structure, such as the toilet and bathroom, and (4) entire buildings that refer to pre-assembled volumetric units forming the actual structure and fabric of the building, such as motel rooms (Gibb, 1999). Prefabricated construction provides an effective alternative to the traditional site-based construction, which improves the productivity, life cycle environmental performance, and predictability of the construction industry and benefits all stakeholders in the construction process (Pan et al., 2012). Compared with the traditional construction technologies, prefabricated construction provides controlled conditions for weather and quality, facilitates the compression of project schedules by changing the sequencing of workflow, and reduces material waste (Li et al., 2014a). Thus, prefabricated construction not only reduces construction waste, noise, dust, operation time, operation cost, labor demand, and resource depletion but also improves quality control, health, and safety (Jaillon and Poon, 2009; Li et al., 2011; Lu et al., 2011; Pan et al., 2007). These advantages significantly improved the performance of the entire construction industry in developed and developing countries, such as the US, the UK, Japan, Singapore, and Mainland China. Given its inherent superiority, precast technology has been improved in China to meet the requirements of sustainability and housing demand. In comparison with the rapid annual increase rate of urbanization, the practice of applying prefabrication technology in the construction industry lags behind. A number of regulations and policies have been promulgated at the national and industrial levels to promote the role and reinforce the importance of offsite production in sustainable development. In the National Plan on New Urbanization 2014–2020 (GOSC, 2014) and Plan on Green Building (MOHURD, 2013), industrialization is one of the most critical issues in the creation of energy-efficient urbanization in China.

Given the precast construction is still in its infancy in China, cost therefore plays a major role influencing the decision-making process when selecting innovative construction methods (Tam et al., 2015; Zhai et al., 2014). Many previous studies placed their emphases on a transparent cost analysis for supporting the feasibility and understanding the prefabrication industry-wide (Kamar et al., 2009; Steinhardt and Manley, 2016). Pan et al. (2008) and Mao et al. (2013a) also highlighted the success of a transparent and systematic costing benchmark in mitigating economic barriers faced by stakeholders and promoting the offsite construction worldwide. In summary, the cost issue is the major factor highlighted from both literature and pilot studies impeding the construction industry to move forward with the precast construction (Blismas et al., 2006; Kamar et al., 2009).

Moreover, in comparison with other regions, there is a necessity to evaluate the cost barrier to the adoption of the precast construction given its foreseeable urgent need in the high-speed urbanization in China. Figure 1 summarized such increased need of the prefabrication by investigating the number of relevant regulations and standards promulgated in China at the provincial level.

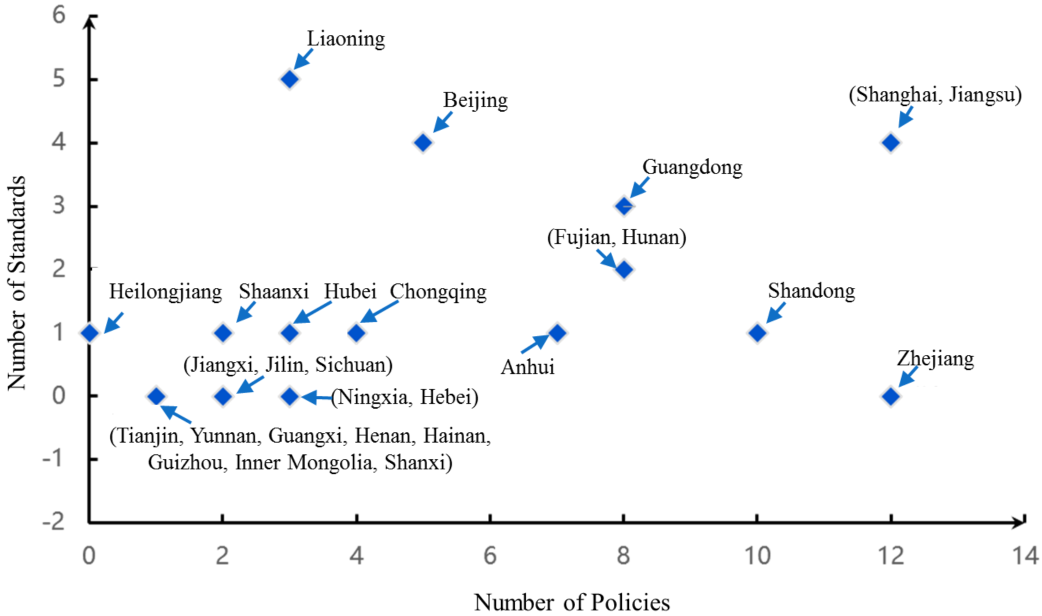

Figure 1 Number of regulations and standards promulgated in China at the provincial level

Apart from this, there are a number of special reasons highlighting the necessity of investigating cost benefits and obstacles of the precast construction in the context of China:

(1) The biggest challenge of hindering the uptake of the prefabrication in China is the cost. This may have arisen from the fact that the perception of cost obstacles grounded in the prefabrication practice is still ambiguous (Mao et al., 2013a; Zhai et al., 2014; Zhang and Skitmore, 2012);

(2) The large population of China may generate the severe shortage of housing while the precast construction provides an attractive and innovative alternative to mitigate such housing demand (Arif and Egbu, 2010);

(3) The cost-related influence factors of the precast construction in the context of China is different from the other countries, including the weakened economies of scale (Mao et al., 2013a), the lower labor cost (Arif and Egbu, 2010), and the lack of skilled workers. Such particular situation in China may cause the cost benefits of the prefabrication as not realistically beneficial.

(4) The quantitative analysis and empirical evidence on specific process data are still scarce as prefabrication is in the early stage in China., which in turn results in the lack of knowledge about the cost assessment method (Chen, 2009; Zhang and Skitmore, 2012).

Therefore, this study develops an analytical framework to facilitate the cost–benefit analysis of prefabricated buildings and to justify the widespread adoption of precast technology in the construction industry. This study initially examined the cost performance of specific prefabricated components by investigating its manufacturing process and other production-related activities and then revealed how the adoption of prefabrication affects the cost profile of real prefabricated buildings by comparing the cost difference between precast and conventional construction. The investigation covers six common prefabricated components used in the context of China, including precast facade, precast form, semi-precast slab, precast staircase, precast balcony, and precast air condition panel.

The specific objectives of this study are outlined as follows:

(1) To decompose the basic cost composition of six common prefabricated components;

(2) To investigate the economic performance of prefabricated buildings in the context of China;

(3) To identify the cost difference between precast and conventional construction;

(4) To explore the driving factors behind the increase in the cost intensity of prefabricated buildings.

Given the significant role and urgent need of precast construction in the high-speed urbanization in China, the findings of this study can generate a transparent and systematic method to assess the cost impact from adopting prefabrication, which enables to advance the construction industry to move forward with the precast construction. The specific contributions include the following aspects. First, a cost-benefit analytical framework is developed to improve the level of industrialization for the betterment of the construction industry as a whole, with due economic considerations. Second, this study examines the cost driving factors in the context of China, which is beneficial to understand the unique in China's construction practice. Third, the empirical results obtained in this study provide a robust evidence of the cost benefits and barriers for the precast construction in China.

The remainder of this paper is organized as follows. Section 2 conducts an overview of the cost barriers in the precast construction. Section 3 presents the basic profile of case buildings. In Section 4, a cost-benefit analysis framework is developed to explore the cost difference between precast and conventional construction method. Section 5 shows the results of cost-benefit analysis in prefabrication. Section 6 presents the discussion, while the conclusions drawn from the study and several research limitations are provided in Section 7.

2. Overview of the cost barriers in precast construction

Precast construction is different from the conventional method in the aspects of building complexity, manufacturing procedures, logistics system, material use, and labor input, which has directly increased difficulties in cost accounting (Chiang et al., 2006; Shen, 2008; Steinhardt and Manley, 2016). In fact, previous studies indicated that the economic performance of the precast construction remains a controversial issue (De La Torre et al., 1994; Gibb, 1999; Steinhardt and Manley, 2016). On the one hand, prefabrication was regarded as one of more cost effective construction method than the traditional one with cost reduction in labor, material, and construction waste (Li et al., 2014b; Tam et al., 2015). Pan and Sidwell (2011) empirically proved the cost-effectiveness of innovative offsite options. Gasparri et al. (2015) held the similar viewpoint by examining the cost of the offsite prefabricated facade. Rogan et al. (2000) also demonstrated that the capital costs could reduce up to 10% by adopting modular construction. Boyd et al. (2012) found the offsite construction offered the cost benefit of up to 30% savings. Also, such cost–benefits encourage the adoption of green technologies that facilitate the use of materials that can be easily reused and recycled in further possible demolition, thereby establishing a positive public image for contractors (Wang et al., 2014). By contrast, Zhai et al. (2014) identified the higher capital cost was a big obstacle to promote the precast construction over the long term. Mao et al. (2016) indicated that the incremental cost of applying prefabrication technique ranged from 27% to 109% in comparison with the conventional construction. Nadim and Goulding (2010) collected the perceptions of offsite construction from industry practitioners by conducting interviews. The results indicated that a widely held perspective on the higher capital costs for offsite construction methods is present in the respondents. By comprehensively reviewing the previous research, this study summarized the major factors influencing the financial performance of the precast construction (See Table 1). In general, the additional costs of highly skilled workers, design changes, initial investment (new machinery, fabricate moulds, and factories), and logistic process were emphasized most. Although extra cost on labor (checking, counting, and sorting raw materials) and components storage space were rarely mentioned, these items indeed generated the direct impact on the economic performance of prefabrication. The primary factors leading to cost savings included the decreased labor requirement on the construction site, enhanced quality of prefabricated components, and Lower maintenance and repair expenses. Labor rate was also highlighted by De La Torre et al. (1994) in the cost savings while, on the contrary, it was identified as the major driver for the cost increase by Khalfan and Maqsood (2014) and Molavi and Barral (2016). Apart from the investigation of the offsite manufacturing process, the research community also argued that it would be more beneficial to identify the cost benefits and barriers in the prefabrication practice from a life-cycle perspective (Gasparri et al., 2015; Jaillon and Poon, 2008; Schoenborn, 2012). However, the relevant studies focusing on the cost saving potential during the maintenance and deconstruction process of prefabricated buildings were still rare given limited empirical data can be found in the realistic cases.

To address such ambiguous perceptions in the cost analysis of precast construction, a number of researchers developed the corresponding cost analytical framework to further examine the cost difference between offsite and conventional construction. Jeong et al. (2017) argued that the major financial advantages of offsite construction lie in the material, construction, and overhead cost. Tam et al. (2015) investigated the cost savings of prefabrication from the aspects including material usage, scaffolding erection, labor force on formwork fixing, concreting, window frame fixing, and window installation. Mao et al. (2016) established a cost analytical framework by dividing all the costs into preliminary, capital, facility management, and disposal cost. However, as a result of the complexity and long-term duration of construction projects and the confidentiality issues stated by clients and contractors, information on building budget is difficult to obtain for further analysis. Such difficulty may be even exaggerated in offsite construction because of its innovativeness in the construction field.

In summary, despite the contribution of previous research to the body of knowledge on the research domain of prefabrication, limited effort has been exerted to develop a cost–benefit analysis framework for prefabricated buildings in the context of China (Zhai et al., 2014; Zhang and Skitmore, 2012; Zhang et al., 2014). Such adoption is a key concern of various stakeholders involved in the construction process and is expected to influence the delivery of prefabricated buildings significantly, which is presently considered the main obstacle that hinders the adoption of prefabrication in China.

Table 1 Factors influencing the economic performance of the precast construction

	Influence factor	Reference
Higher cost	Highly skilled workers	[1], [2], [3], [4], [5], [6], [7]
	Complex techniques	[1], [8], [2], [9]
	Complex design	[1], [10], [2], [11], [3], [12], [9], [13]
	Additional procurement costs	[10], [5]
	High initial cost (cost on new machinery, fabricate molds, and factories)	[8], [14], [14], [12], [15], [16], [17], [6], [13], [7]
	Extra labor cost on checking, counting, and sorting raw materials	[18]
	Occupying extra space for accommodation of precast components	[14]
	Additional transportation costs	[14], [9], [19], [15], [20], [6]
	Additional use of tower cranes (vertical transportation)	[14], [6]
Lower cost	Increased productivity	[21], [14], [12]
	Decreased labor	[21], [10], [22], [14]
	Avoidance of construction site hindrances	[10]
	Cheaper labor rates	[10]
	Decreased management cost	[10]
	Faster project delivery	[10]□, [22]
	Minimal wastage	[8], [14], [6]
	Less site materials	[8], [7]
	Reduction of formwork	[22]

	Controlled quality	[22], [8], [14], [12], [6]
	Lower maintenance and repair expenses	[7], [15], [23], [24]

Note: [1] Molavi and Barral (2016); [2] Thanoon et al. (2003); [3] Jaillon and Poon (2009); [4] Khalfan and Maqsood (2014); [5] Zhang and Skitmore (2012); [6] Chiang et al. (2006); [7] Zhai et al. (2014); [8] Kamar et al. (2009); [9] Shen (2008); [10] De La Torre et al. (1994); [11] Gasparri et al. (2015); [12] Zhang et al. (2014); [13] Luo et al. (2015); [14] Tam et al. (2015); [15] Jaillon and Poon (2008); [16] Pan et al. (2007); [17] Pan et al. (2008); [18] Zhong et al. (2015);[19] Lu and Yuan (2013); [20] Mao et al. (2013a); [21] Gibb (1999); [22] Schoenborn (2012); [23] Polat (2008); [24] Jaillon and Poon (2010).

3. Case study and data consolidation

The selection criteria for the target case buildings in this study include:

(1) The selected buildings should be built with a similar building type, structural system, and other profiles that may cause the changes in the project budget.

(2) The target buildings should cover a broad range of prefabrication rate and adopt several types of prefabricated building components. Such settings can facilitate an in-depth investigation of cost effect from the precast construction.

(3) This study assumes that the effect of cost variations induced by the onsite construction management skill is negligibly small on the total cost.

Based on criteria above, a field survey is conducted through the combined methods of site investigation, questionnaire, and face-to-face interviews with designers, project managers and prefabrication suppliers associated with the target projects. The questionnaire comprises three parts as summarized in Table 2. The first part is designed to understand the basic profile of the target prefabricated building. The second part represents the prefabrication information including the volume of prefabrication, prefabrication rate, and volume of each type of prefabricated component used in the target project, which aims to explore the features of the sample prefabricated buildings and establish the quantitative basis for cost estimation. The third part investigates the cost information for different lifecycle stage of buildings, namely, design, offsite manufacturing, transportation, and on-site construction, which aims to facilitate the comparison with the conventional buildings.

In summary, although the collection of budget data is relatively difficult because of the confidential nature of the construction industry, basic cost information of eight prefabricated buildings was eventually collected.

Table 2 Description of the questionnaire

Part	Content	Detail
Part I	Basic information	Location, building type, gross floor area, total cost
Part II	Prefabrication information	Volume of prefabrication, prefabrication rate, volume of prefabricated components used
Part III	Cost information	Cost on design, offsite manufacturing, transportation, and onsite construction

Based on the field survey, the basic profiles of the sample buildings labelled from R1 to R8 are shown in Table 3. All of the buildings were residential buildings with the same frame shear structure. This consistency in building type and structure enables comparability to a certain extent. By contrast, a number of building parameters, such as the gross floor area and volume of prefabrication, vary among sample buildings. These profiles may directly determine the economic performance of a certain building, which enables the investigators to examine the cost-effectiveness of offsite construction. In this study, the precast rate is defined to describe the percentage of prefabrications in the total volume of concretes used in the target building, which has been regarded as an efficient variable to reflect the prefabrication level of a building.

Two categories of data, namely, process-based inventory data for offsite manufacturing and basic design parameters of investigated building projects, were required in this study. The process-based inventory data for six common prefabricated components are summarized in Table 4, with a full breakdown including material use, labor input, machine use, miscellaneous works, transportation, and profit and tax. More importantly, the superiorities and limitations of adopting prefabricated construction were discussed during the interviews. A number of immeasurable expenditures were also estimated based on their professional experience. The quantitative data collected from the field survey through case studies can serve as firsthand data and an effective method to understand the cost performance of prefabricated buildings. In this study, the focus of concern is on prefabricated residential buildings as the current development of precast construction remains backwards in China, where the application of prefabricated technologies in public buildings is scarce.

Finally, a number of techniques were adopted to normalize the raw data and ensure the comparability of sample buildings. First, the preliminary cost on land development and acquisition was assumed to be similar for the same building regardless of the construction method adopted. The capital cost of building decoration and demolition was excluded in the cost discussion to establish a common base for further analysis. Second, the unit price of materials and machine for an identical building was assumed to be the same between conventional and precast scenarios. Third, the costs were all converted into the 2015 constant prices via price indices to keep the price consistent. Fourth, multiple measurement units, such as cost intensity of prefabrication (yuan/m^3) and cost intensity on a per-square-meter basis (yuan/m^2), were employed to build a general base for the cost-effective comparison.

Table 3 Building profiles of the eight sample buildings

		Unit	Sichuan			Shanghai		Shenzhen		
			P1	P2	P3	P4	P5	P6	P7	P8
Building basic	Building type		R	R	R	R	R	R	R	R

information	Structure		FSS	FSS	FSS	FSS	FSS	FSS	FSS	FSS
	Gross floor area	m^2	7,770	6,890	38,352	9,467	7,039	28,522	13,600	8,000
	Total cost	Million yuan	15.8	16.6	61.7	19.1	14.8	43.9	40.3	38.1
Prefabrication technology	Volume of prefabrication	m^3	933	1,250	2,891	1,089	804	1,740	2,312	2,080
	Precast rate	%	41	59	20	40	44	15	40	60
	Precast facade	m^3	850	769	0	0	415	1,296	1,195	1,127
	Precast form	m^3	0	0	0	811	0	0	229	0
	Semi-precast slab	m^3	0	401	2,240	0	265	0	563	574
	Precast balcony	m^3	28	55	498	167	74	301	138	82
	Precast staircase	m^3	32	26	153.4	89	36	142	187	297
	Precast air condition panel	m^3	24	0	0	22	7	0	0	0

Note: FSS represents the frame shear structure

Table 4 Decomposition of the basic cost for six prefabrications

	Unit	Precast facade	Precast form	Semi-precast slab	Precast balcony	Precast staircase	Precast air condition panel
Thickness	mm	180	85	70			
Concrete	m^3	0.9	0.98	0.84	0.84	0.84	0.84
Steel	kg	131	119	152	285	133	161
Embedded part	kg	142	121	0	31	11	25
Template use	yuan	128	247	300	95	224	95
Labor cost	yuan	544	770	783	439	439	439
Construction machine use	yuan	24	52	57	22	22	22
Maintenance	yuan	49	97	114	50	50	50
Finish protection	yuan	30	64	71	20	20	20
Transportation	yuan	207	437	214	180	202	180
Profit and tax	yuan	639	776	628	643	463	486

4. Development of cost–benefit analysis framework

In previous research, most of the cost-related studies focused on the overall cost investigation rather than considering the prefabricated part separately. A cost–benefit analysis framework, particularly for prefabricated buildings, was conceptualized and developed to provide a holistic understanding of the cost-effectiveness of prefabrications to address such weakness. The total cost of prefabricated buildings has been further decomposed into four categories, namely, design, prefabrication part, cast-in-situ part, and onsite construction, to distinguish the difference between precast and conventional construction.

4.1 Cost for design (C_1^p)

According to the field survey, interviewees also emphasized that prefabrication is a relatively new and innovative technology applied in the construction process; thus, it needs to be elaborately designed and scheduled in advance. This process is indispensable and can be taken as a premise for prefabrication application, particularly in China where the necessary practical experience and professional guidance are lacking. Therefore, in addition to the expenses in manufacturing, transportation, and on-site construction process, extra cost needs to be paid for the additional service provided by the professional consultant (e.g., architect, quantity surveyor, and engineer) and designer. The major additional services provided in the pre-construction stage, as mentioned by the interviewees, are summarized in Table 5.

Table 5 Additional services in the pre-construction stage of precast construction

Additional service	Features
Drawing work (C_{11}^{p})	The number of drawings is 3–5 times that of the conventional construction method
Labor input (C_{12}^{p})	The labor force is 2–4 times
Design cycle (C_{13}^{p})	The period for the design stage is 1.5–2 times
Offsite production guidance (C_{14}^{p})	Additional professional fees of architect, quantity surveyor, and engineer
Conflict examination (C_{15}^{p})	Professional 3D software is needed for collision check
Bidding (C_{16}^{p})	Additional bidding fee for prefabrication suppliers

4.2 Cost for prefabricated part (cost for cast-in-situ counterpart) (C_{2}^{p})

In previous research, cost estimation in related studies was mostly based on the interview or questionnaire instead of systematic quantitative analysis. This study aims to fill these research gaps using the firsthand qualitative and quantitative data collected through field survey. Jaillon and Poon (2009) indicated that the major type of prefabricated components used in the Hong Kong construction industry includes precast facades, semi-precast slabs, precast staircases, precast beams and structural walls, precast bathrooms, precast kitchens, precast balconies, and precast internal partitions. Precast façades, partition walls (drywall) parapet, staircases, and semi-precast slabs are the most commonly adopted precast elements. Some pilot projects have even adopted complicated volumetric precast units, such as precast volumetric kitchen and bathroom and structural walls to extend the precast component coverage to 65% (Tam, 2007). Mao et al. (2013b) investigated the greenhouse gas (GHG) emissions from three common prefabricated components, namely, facades, staircase, and slabs. Given the current development of prefabrication technology and the data availability in China, this study focuses on six typical types of prefabricated components, which are regarded as the major prefabrications used in the building construction in China.

This study divided the basic cost of prefabricated components into the following six items for further economic investigation: cost of the main materials (C_{21}^{p}), labor input (C_{22}^{p}), machine use (C_{23}^{p}), miscellaneous work (C_{24}^{p}), transportation (C_{25}^{p}), and profit and tax (C_{26}^{p}). In this study, miscellaneous work, which is necessary for a temporary component store, involves daily maintenance and protection after manufacturing in the offsite factory. Transportation for precast construction includes two steps, namely, moving raw materials to the fabrication plant and transporting prefabricated components to the construction site. This systematic logistics process has considerable challenges, not only requiring an appropriate plan for the on-time delivery of materials and components but also needing additional protection of loading and fixation when transporting prefabricated components. Moreover, paying extra cost to clients or contractors in improving the quality of onsite road and extending the paved road area for prefabrication transportation are necessary. According to Lu and Yuan (2013), the average cost for prefabrication transportation takes up 18% to 20% of the total cost. With regard to the cost of wastage in the manufacturing process, prefabricated construction has been considered a key strategy to promote construction waste reduction (Baldwin et al., 2009). Tam et al. (2007) also indicated that one effective method to reduce building wastage generation is to apply prefabrication in the building. In contrast to the traditional construction method where executing concrete casting and assembly works in the confined area is the process, the manufacturing of prefabrication benefits from industrialized mass production can handle and store building component precisely, resulting in approximately zero wastage in the manufacturing process. According to the survey conducted by Lu and Yuan (2013), the wastage level in the prefabrication transportation process is also approximately zero because of few damages in this process. Therefore, the percentage of waste materials in the upstream process of precast construction is significantly small. In fact, Lu and Yuan (2013) indicated that the wastage rate of the major materials consumed in the manufacturing process is lower than 2% by weight. By contrast, the percentage of wastage materials in the conventional construction method is comparatively high. Table 6 summarizes the wastage rate of common building materials used in previous research. Concrete and steel bar, as the two major materials used in the manufacture of prefabrication, were wasted from approximately 7% to 8% in the conventional construction process. However, according to Tam et al. (2007) and Jaillon and Poon (2009), using prefabricated components minimizes more than 50% of construction waste. In addition, the unit price should be a comprehensive price, which contains the tax and retailer profit. Therefore, according to interviewees, we assume that the profit and tax were equal to

25% of the cost of materials, labor, and machine.

Table 6 Wastage rate of typical building material

	Conventional construction			Prefabrication
	Blengini (2009)	Poon et al. (2001)	Tam et al. (2007)	
Concrete	7%	3–5%	4–7%	0.5–3.5%
Steel bar	7%	1–8%	3–8%	0.2–4%
Timber	7%	5–15%	4–23%	0.6–12%
Block/brick	10%	4–8%	5–8%	0.6–4%

4.3 Cost for cast-in-situ part (C_3^p)

In the prefabricated building system, additional materials are necessary to combine prefabrication and cast-in-situ part to ensure the quality and integrity of the entire building, particularly in comparing with the conventional construction method. For instance, steel-made connectors and fixings are commonly used in the joint part to connect prefabrications and cast-in-situ concrete. Additional reinforced steel should also be provided in the interface when pouring purchased concrete to prevent cracking. Consequently, the steel intensity of the cast-in-situ part between precast and conventional buildings is different. According to Li (2012), the amount of steel used in prefabricated buildings is 10% to 60% more than that in conventional buildings.

4.4 Cost for onsite construction (C_4^p)

According to the interviews with contractors, prefabricated components are manufactured in the factory separately and considered for onsite assembly in the general situation. On the one hand, some cost–benefits can be obtained from the use of prefabrication instead of purchasing cast-in-situ concrete. For instance, the onsite installation of windows and doors in the conventional construction method is replaced by preinstallation in the offsite factory. Also, from the perspective of onsite management, the standardization and uniformed design of prefabrication enable clients to improve construction efficiency and maximize material utilization by reducing engineering changes, maintenance expenses, and wastage generation during the building construction process. By contrast, the considerable extra cost has been spent on additional works associated with onsite installation and subassembly works, such as horizontal transportation and vertical lifting, during the building construction process. Additional miscellaneous works, such as unloading, protection, and storage prefabrication, are also required for precast construction. These manipulations need assistance from advanced construction technologies and additional equipment, which may increase cost.

In summary, from the aforementioned cost categories and differences with the conventional construction method, the cost–benefit analysis framework can be developed, as shown in Figure 2.

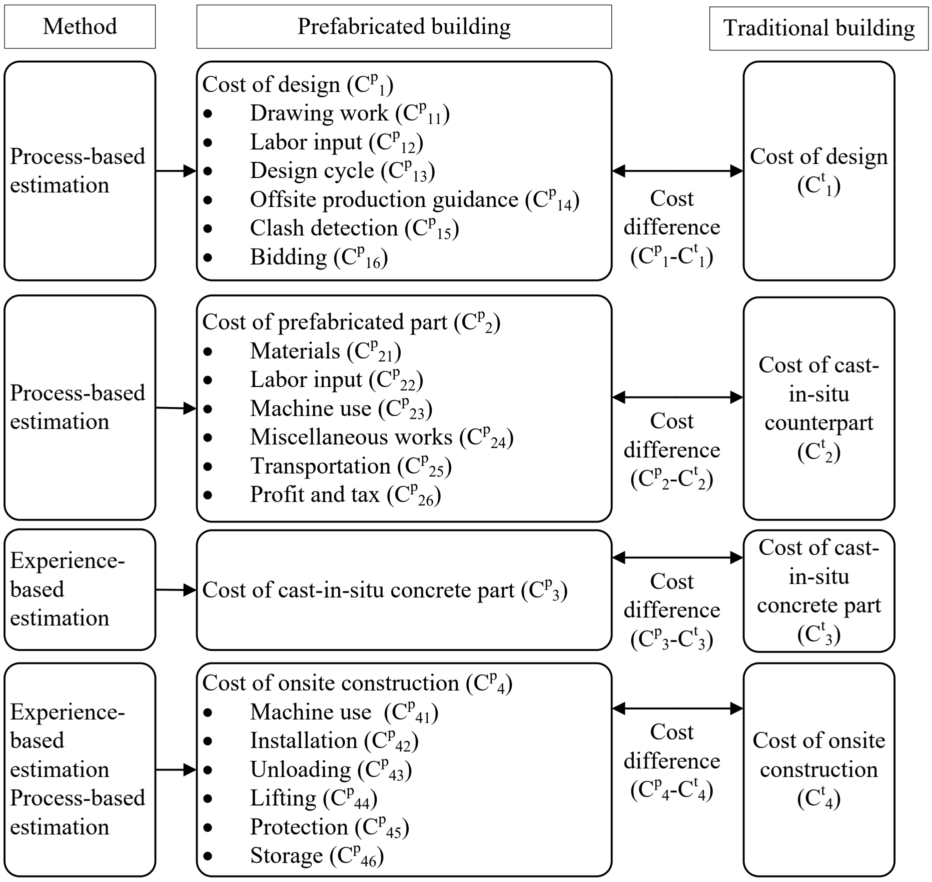

Figure 2 Cost–benefit analysis framework

5. Analysis of the results

5.1 Cost decomposition of common prefabricated building components

A cost breakdown of the target prefabricated components is shown in Figure 3. During the fabrication process, material use is identified as the major contributor to the total cost. The quantity of steel is to a large extent dependent on the basic function and structure requirement of a particular type of prefabrication, but still contributes most to the total cost because of its large quantity and comparatively high unit price in building the material market. Generally, concrete and steel are responsible for 30% to 55% of the total cost. In addition to the cost of material use (e.g., steel and concrete), labor input also plays an important role in the economic performance of prefabrications, accounting for 14% to 24% of the total cost. More importantly, compared with the traditional construction method, additional expenses are needed for miscellaneous works, such as finish protection, offsite maintenance, storage, and transportation. In contrast to the conventional material transportation process, the logistics of prefabrications requires a careful load–unload control process and additional protection and fixation to avoid possible damage during transportation. In this study, the cost of transportation ranges from 6% to 11%. Lu and Yuan (2013) indicated that the overall expenses of prefabricated components transported from Guangdong to Hong Kong took up 18% to 20% of the total cost after interviewing people from prefabrication companies. This percentage occurred under the cross-border transportation, which may be slightly higher than the normal situation. Therefore, the proportion obtained from this study is reliable and valid. In summary, typical structural bearing components (e.g., precast form and facade) and cantilevered structure (e.g., precast balcony) are more steel-intensive, which leads to a relatively higher unit price. By contrast, the cost of precast staircases and air conditioning panel is comparatively low.

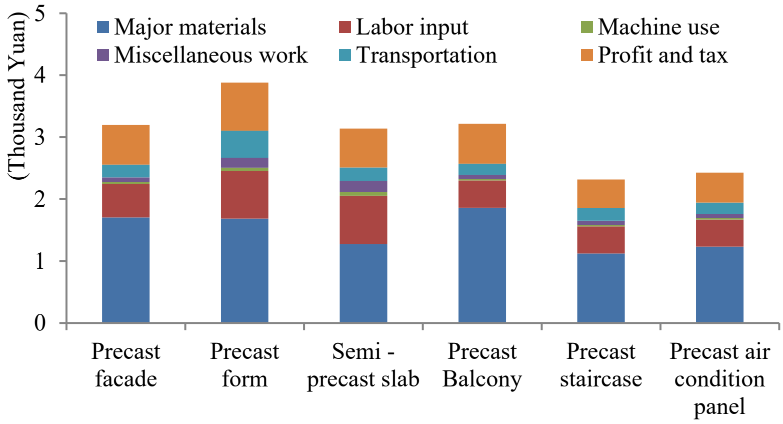

Figure 3 A cost breakdown of the target prefabricated components

5.2 Cost examination of prefabricated buildings

A number of studies indicated that the unit cost of prefabricated buildings was estimated as 2% to 17% higher than the conventional buildings (Lu and Yuan, 2013; Jaillon and Poon, 2008). Therefore, investigating the drivers behind the incremental cost from adopting prefabrication technology during the building construction process is necessary. Figure 4 presents a breakdown of the total cost intensity of eight prefabricated buildings by reordering the sample buildings according to their precast rate. The cost intensity was generally positively correlated with the precast rate. In other words, the extent of prefabrication adopted directly determines the cost-effectiveness of buildings. Mao et al. (2016) made a similar conclusion that a higher percentage by precast volume resulted in a higher cost. Meanwhile, the cost of the prefabricated building envelope (e.g., precast facade and form) is the major driver of the cost incremental when compared with other types of prefabricated components.

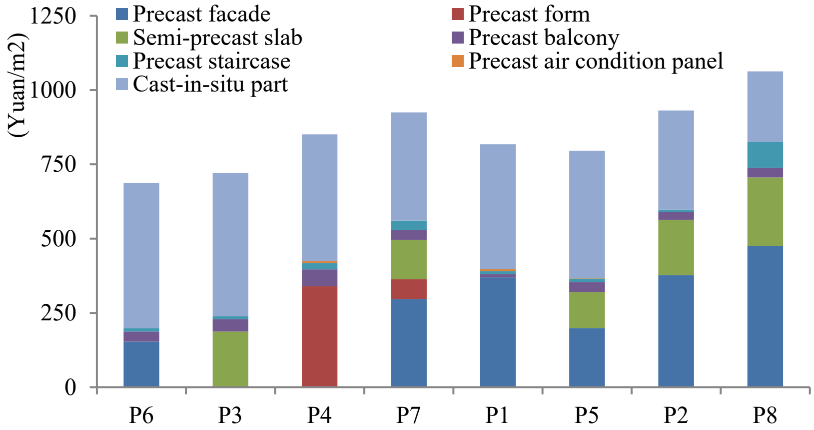

Figure 4 A breakdown of the total cost intensity of eight prefabricated buildings

A series of regression analyses were conducted to further explore the relationship between precast rate and cost intensity of prefabricated buildings. The results showed that the total cost intensity (Figure 5) and incremental cost intensity (Figure 6) were significantly positively correlated with the precast rate of the eight target buildings. Therefore, the improvement of prefabrication utilization forgoes the current economic benefit in China. Such heavy cost burden from adopting the prefabrication technology has impeded the promotion of precast construction in China.

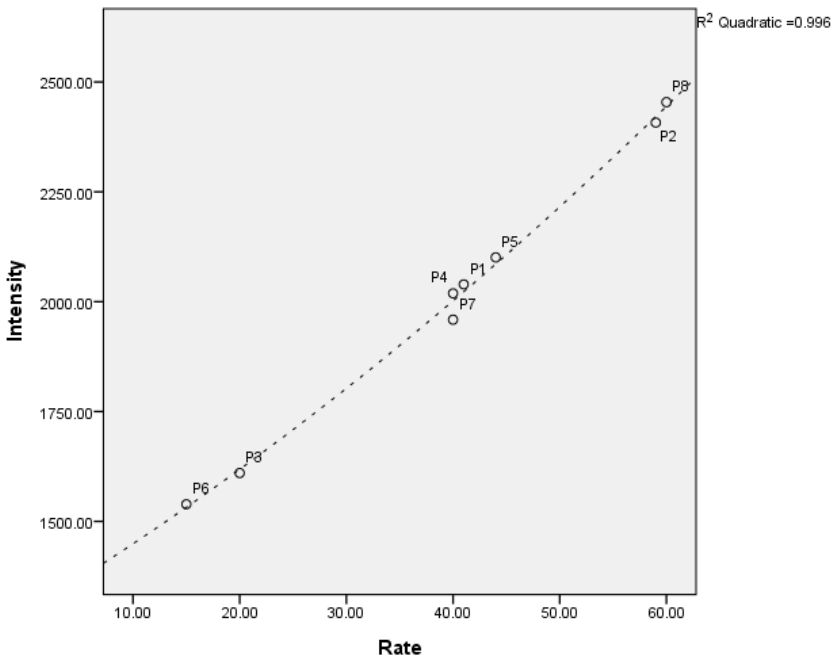

Figure 5 Regression analysis of total cost intensity and precast rate

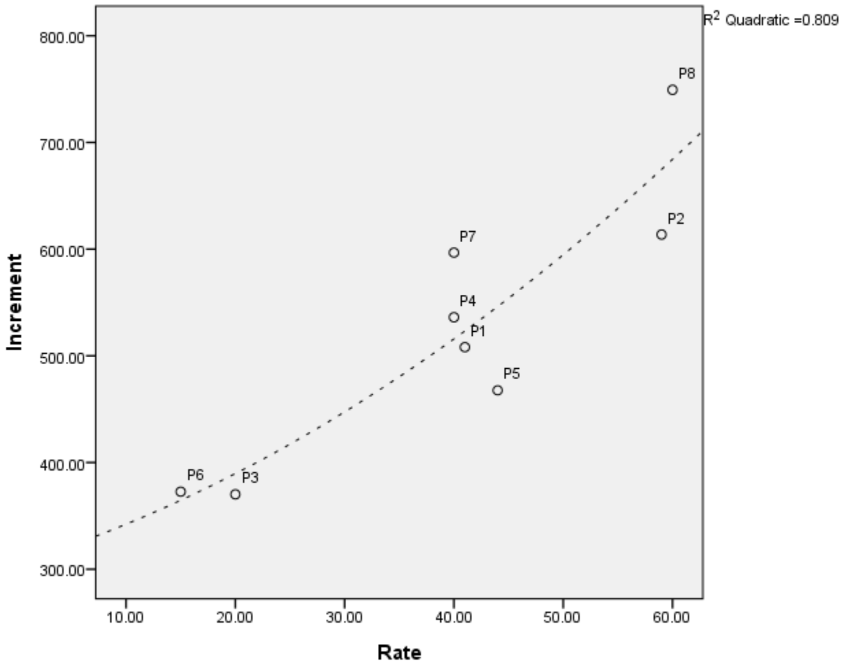

Figure 6 Regression analysis of incremental cost intensity and precast rate

A comparative analysis was conducted under the precast and conventional scenarios based on the cost items listed in the analytical framework to explore the main drivers behind the cost increase of prefabricated buildings. Figure 7 shows the cost intensity of prefabricated buildings and conventional counterparts. Buildings constructed under prefabrication technology were 26.3% to 72.1% higher than those built with the traditional model, ranging from 372 yuan/m^2 in Project 6 to 1,028 yuan/m^2 in Project 8. Mao et al. (2013a) made a similar conclusion that the adoption of precast construction caused 20% higher than the total cost of using conventional construction method. Figure 8 examined the effect of four cost categories under the cost–benefit analysis framework on the total incremental cost for eight case buildings. Notably, the manufacturing of prefabrications is dominant in the total incremental cost, ranging from 32.3% to 63.3% in all sample buildings. Such dominance is primarily induced by the cost occurred in the additional materials and works, such as the use of embedded parts, additional miscellaneous work, and challenging logistics process. Given the higher traffic volume than the conventional model and the additional efforts focused on fixation and onsite road preparation, the transportation cost increased by approximately 10%. The second driver behind the cost increase is onsite construction, including machinery cost (vertical transportation), installation, jointing, and onsite storage. Mao et al. (2016) also emphasized the importance of additional lifting in precast construction by demonstrating a higher frequency of the use of tower cranes. Moreover, given the difficulties in the scheduling of the design–manufacturing–assembly process, reserving onsite waiting space for prefabricated components in construction practice is quite normal. Such temporary storage should be conducted with considerable care and also needs additional efforts and cost (Tam et al., 2015). By contrast, the additional cost occurred in the design and cast-in-situ counterpart was negligibly small. Although the complex design was identified as a major factor causing increased cost (Gasparri et al., 2015; Luo et al., 2015; Molavi and Barral, 2016), this part was insignificant because of a relatively lower labor cost in the context of China. The consultant services and drawing work in the design stage resulted in a 4.7% to 12.9% increase, whereas the material changes in the cast-in-situ counterpart only increased 1.6% to 4.3% of the total cost.

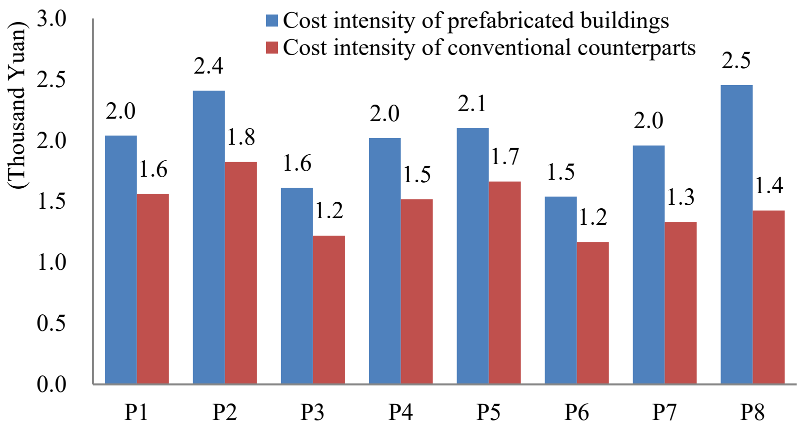

Figure 7 Cost intensity of buildings constructed under prefabricated and conventional scenarios

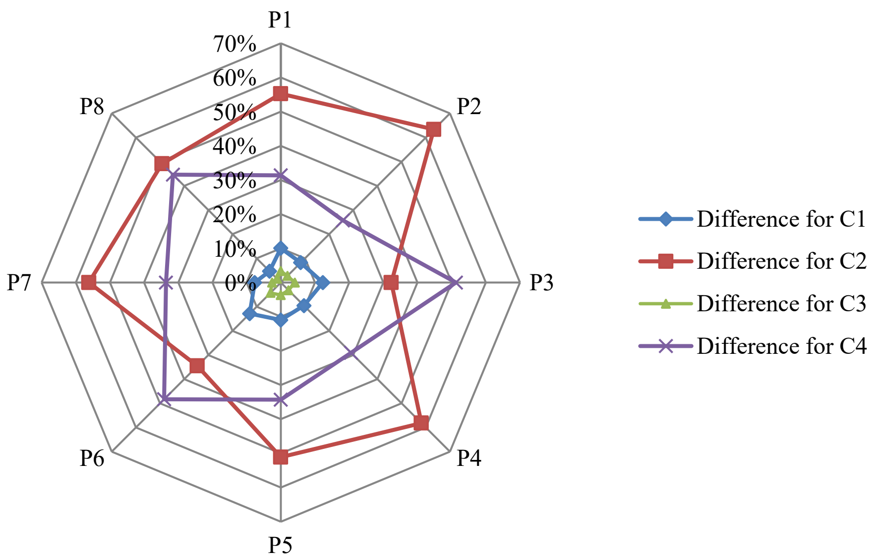

Figure 8 Proportion of four cost categories in the total incremental cost

In summary, the total cost intensity of prefabricated buildings is significantly positively correlated with the precast rate. The manufacturing of prefabrications contributed most to the total incremental cost, followed by the onsite assembly, whereas the additional cost incurred in the design and cast-in-situ counterpart has only a slight effect.

5.3 Examination of the effect of geographical location

The influence of the change of geographical location on the cost intensity of prefabricated buildings can be further examined by keeping other variables static. Table 1 shows that Projects 1, 4, and 7 were built under the same building type, structure system, and precast rate and distributed in Sichuan, Shanghai, and Shenzhen, respectively. Therefore, a detailed comparative analysis of these three buildings could help to examine the possible effect of geographical location on the total cost. The results showed that the incremental cost intensity was highest in Project 7, followed by Projects 4 and 1. This finding relates primarily to the fact that the unit price of materials and labor force is relatively higher in developed regions (e.g., Shenzhen and Shanghai) than that in developing regions (Sichuan). More specifically, Shenzhen is located in the Pearl River Delta Region, which is identified as the major supplier for the prefabrication sector in the surrounding regions, such as Hong Kong. Consequently, the proper facilities, services, and factories necessary for the entire supply chain of prefabricated housing production are well established. Such maturity in the construction market of Shenzhen can to a large extent reduce unnecessary preliminary cost during the design, manufacturing, and transportation stages, which result in a relatively lower unit price than prefabricated projects in Shanghai.

6. Discussions and policy implications

According to the findings, three critical factors influencing the cost-effectiveness of prefabricated buildings in the context of China can be summarized. The factors are as follows: precast rate, types of prefabricated components adopted, and market maturity of the local construction market.

Given the economic impact of precast rate is rarely investigated in previous studies, this study provides solid evidence for the tight linkage between the cost overrun and precast rate of building projects. The promotion of precast construction may sacrifice the economic benefits of the construction projects, which is bound to increase the reluctance of clients in implementing prefabrication technology because they are profit-oriented and cost-sensitive in the construction market. A number of cost-saving strategies should be adopted to resolve this dilemma. Maximizing the utilization of offsite fabrication to improve cost efficiency through mass production is recommended. Only continuous bulk orders can make the full use of cost benefit from economics of scale. This technique can not only minimize production time and disturbance in the offsite factory but also enhance the rationalization of the procedures along a production line.

Second, the significant role of the prefabrication manufacturing process in the cost accounting was highlighted in the present study, which is also rarely identified in previous research. This may have arisen from the fact that handicraft operation is widespread in the offsite factory in the context of China. This requires a tool-based or automatic production system in the fabrication plant to minimize such high capital cost during the manufacturing process.

Third, the findings of this study show that despite the preference of government policy and promising future of prefabrication in the construction industry, the concept of industrialization is only applied to a small part of building components. According to the interviews, precast slab, precast staircase, and precast balcony are prioritized to precast facade and form with regard to the current practice in China. This practice is mainly because the unit price of the prefabricated building envelope is higher that its counterparts in the traditional construction method. In other words, other cost-effective alternatives, such as block or brick-made external walls, are prioritized to concrete-made external walls for the nonbearing structure. However, for the places that may be more likely vulnerable to damages from typhoon and extreme weather, such as Hong Kong, a prefabricated building envelope with a higher integrality and quality should be selected to ensure safety. Moreover, in addition to a higher cost, the precast building envelope is also energy-intensive according to the study of Hong et al. (2016). Therefore, developing multi-performance materials, which are not only environment-friendly but also cost-effective for prefabricated components, is challenging but necessary.

Fourth, the extent of industrialization of the construction market in a particular region also indirectly influences the cost intensity of prefabricated buildings. The lack of necessary prefabrication facilities, experienced stakeholders, and prefabrication suppliers can increase the preliminary cost in the upstream process of building construction. In fact, according to the interviews, such hidden cost is particularly significant, which is estimated to be 120 yuan/m^2 to 150 yuan/m^2. Interviewees emphasized that a mature construction market with highly evolved industrialization enables the effective reduction and management of the cost incurred in the preliminary stage. Therefore, the immaturity of the prefabrication market is another barrier in the current practice given the backwards development of precast construction in China.

Moreover, although the unit cost was estimated relatively higher in the embodied phase of prefabricated buildings, earning the cost–benefit in the operational phase is still promising. Factory production provides a controlled condition to maximize quality by concentrating on a single element without distraction from a collection of parts and fixations, thereby improving durability to avoid recurrent maintenance and renovation. Moreover, with tool-based assistance and automatic control during the manufacturing process, the precision of components can be further improved to minimize potential conflicts in the onsite installation and reduce the frequency of replacement in the building operational phase.

Recognizing the cost–benefit of the precast industry is of importance in providing a better understanding of the economic property of prefabrication and promote the industrialization of building construction in China. Therefore, implementing the corresponding policies to address the economic barriers identified in this study is crucial. First, the empirical results reveal the implications of the current cost performance of prefabricated buildings in China. Given the ranges of incremental cost by adopting different types of prefabrications, the local government can provide financial support with different levels of subsidies not only for stakeholders but also for suppliers to encourage the application of prefabrication technology. Such incentive can make a rapid return on the cash flow for clients, which is essential for the operation of their companies. Second, policies should be biased toward improving the maturity of the precast market because offsite production is still in an initial stage in China. The local government should promulgate technical guidance, build the corresponding facilities, attract experienced stakeholders, encourage professional suppliers, and train specialized workers in the property market, which could effectively facilitate the implementation of prefabrication technologies at the pre-construction stage, reducing additional cost spent on prophase investigation. Third, given a relatively higher proportion of component manufacturing in the total cost changes for prefabricated buildings, replacing manual operations with computer-based or tool-based control systems to enhance the level of automation, ensure the precision, and improve the productivity of the manufacturing process is imperative.

7. Conclusions

In summary, a cost–benefit analysis framework has been established to examine the cost performance during the prefabrication design, manufacturing, transportation, and on-site installation processes holistically. Empirical studies were employed to assess the cost-effectiveness of adopting precast construction in real building cases. The results can be regarded as a solid reference point from which to re-recognize the backwards development of the precast industry in China. The key findings are as follows:

(1) Material use is identified as the major contributor to the cost of prefabrications, where concrete and steel are responsible for 30% to 55% of the total cost, followed by labor input (14% to 24%) and transportation (6% to 11%). Moreover, the cost is

involved additional miscellaneous works, such as finish protection, offsite maintenance, and storage of completed prefabrications.

(2) The cost intensity of prefabricated buildings was estimated 26.3% to 72.1% higher than that of conventional buildings, which was significantly positively correlated with the precast rate. The manufacturing of prefabrications contributed most to the total incremental cost, accounting for 32.3% to 63.3% of total cost changes. The second driver behind the cost increase is onsite construction, whereas the additional cost incurred in the design and cast-in-situ counterpart has only a slight effect.

(3) The level of maturity in the local construction market directly determines the cost-effectiveness of precast construction. The preliminary cost spent on the upstream process of prefabricated buildings is estimated to be 120 yuan/m^2 to 150 yuan/m^2 for building necessary facilities.

In summary, providing financial support for implementing prefabrication technology, improving the maturity of the precast construction market, adopting computer-based or tool-based control systems, and developing multi-performance materials should be considered for further development of prefabrication in China. The empirical analysis in this study allows identification of a wide range of driving factors behind the increased cost of using prefabrication, but the findings may be restricted by the number of sample buildings investigated and contextual factors when it is applied in a more generic way. More specifically, a systematic investigation of sufficient building cases can minimize the inherent uncertainty from initial assumptions like assuming a similar level of onsite management skills among different prefabricated buildings, thus further enhancing the reliability of obtained findings. The contextual factors like the geographical location may determine the local market maturity, which has a direct impact on the initial cost of using prefabrication. Consequently, apart from extending the analysis framework into a boarder scope, future research should also focus on quantifying the economic gains by adopting proposed optimization strategies, including using automatic control system in the manufacturing process, enhancing the prefabrication-oriented supply chain, and providing financial support or planning credits by the local government.

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References

Arif, M., Egbu, C., 2010. Making a case for offsite construction in China. Engineering, Construction and Architectural Management 17, 536-548.

Baldwin, A., Poon, C.-S., Shen, L.-Y., Austin, S., Wong, I., 2009. Designing out waste in high-rise residential buildings: Analysis of precasting methods and traditional construction. Renewable energy 34, 2067-2073.

Blengini, G.A., 2009. Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. Building and Environment 44, 319-330.

Blismas, N., Pasquire, C., Gibb, A., 2006. Benefit evaluation for off-site production in construction. Construction Management and Economics 24, 121-130.

Boyd, N., Khalfan, M.M., Maqsood, T., 2012. Off-site construction of apartment buildings. Journal of Architectural Engineering 19, 51-57.

Chen, W., 2009. Analysis on Housing Industrialization Restrainging Factors from SST Perspective [J]. Shanxi Coking Coal Science & Technology 5, 014.

Chiang, Y.-H., Hon-Wan Chan, E., Ka-Leung Lok, L., 2006. Prefabrication and barriers to entry—a case study of public housing and institutional buildings in Hong Kong. Habitat International 30, 482-499.

De La Torre, M.L., Sause, R., Slaughter, S., Hendricks, R.H., 1994. Review and Analysis of Modular Construction Practices.

Gasparri, E., Lucchini, A., Mantegazza, G., Mazzucchelli, E.S., 2015. Construction management for tall CLT buildings: From partial to total prefabrication of façade elements. Wood Material Science & Engineering 10, 256-275.

Gibb, A.G., 1999. Off-site fabrication: prefabrication, pre-assembly and modularisation. John Wiley & Sons.

GOSC, 2014. National Plan on New Urbanization 2014-2020, in: China, G.O.o.t.S.C.o.t.P.s.R.o. (Ed.), Beijing, China.

Jaillon, L., Poon, C.-S., 2008. Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study. Construction Management and Economics 26, 953-966.

Jaillon, L., Poon, C.S., 2009. The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector. Automation in Construction 18, 239-248.

Jaillon, L., Poon, C.S., 2010. Design issues of using prefabrication in Hong Kong building construction. Construction Management and Economics 28, 1025-1042.

Jeong, J., Hong, T., Ji, C., Kim, J., Lee, M., Jeong, K., Lee, S., 2017. An integrated evaluation of productivity, cost and CO 2 emission between prefabricated and conventional columns. Journal of Cleaner Production 142, 2393-2406.

Kale, S., Arditi, D., 2006. Diffusion of ISO 9000 certification in the precast concrete industry. Construction Management and Economics 24, 485-495.

Kamar, K., Alshawi, M., Hamid, Z., 2009. Barriers to industrialized building system (IBS): The case of Malaysia, In BuHu 9th International Postgraduate Research Conference (IPGRC), Salford, United Kingdom.

Khalfan, M., Maqsood, T., 2014. Current state of off-site manufacturing in Australian and Chinese residential construction. Journal of Construction Engineering 2014.

Li, H., Guo, H., Skitmore, M., Huang, T., Chan, K., Chan, G., 2011. Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong. Construction Management and Economics 29, 233-245.

Li, J., 2012. Advantages and disadvantages analysis andsuggestion on the PC system of present residence's main structure. China Academic Journal Electronic Publishing House, 24-29.

Li, Z., Shen, G.Q., Alshawi, M., 2014a. Measuring the impact of prefabrication on construction waste reduction: An empirical study in China. Resources, Conservation and Recycling 91, 27-39.

Li, Z., Shen, G.Q., Xue, X., 2014b. Critical review of the research on the management of prefabricated construction. Habitat international 43, 240-249.

Lu, W., Huang, G.Q., Li, H., 2011. Scenarios for applying RFID technology in construction project management. Automation in Construction 20, 101-106.

Lu, W., Yuan, H., 2013. Investigating waste reduction potential in the upstream processes of offshore prefabrication construction. Renewable and Sustainable Energy Reviews 28, 804-811.

Luo, L.-z., Mao, C., Shen, L.-y., Li, Z.-d., 2015. Risk factors affecting practitioners' attitudes toward the implementation of an industrialized building system: A case study from China. Engineering, Construction and Architectural Management 22, 622-643.

Mao, C., Shen, Q., Pan, W., Ye, K., 2013a. Major Barriers to Off-Site Construction: The Developer's Perspective in China. Journal of Management in Engineering 31, 04014043.

Mao, C., Shen, Q., Shen, L., Tang, L., 2013b. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. Energy and Buildings 66, 165-176.

Mao, C., Xie, F., Hou, L., Wu, P., Wang, J., Wang, X., 2016. Cost analysis for sustainable off-site construction based on a multiple-case study in China. Habitat International 57, 215-222.

Meiling, J.H., Sandberg, M., Johnsson, H., 2013. A study of a plan-do-check-act method used in less industrialized activities: two cases from industrialized housebuilding. Construction Management and Economics, 1-17.

MOHURD, M.o.H.a.U.-R.D.o.t.P.s.R.o.C., 2013. Plan on Green Building. National Development and Reform Commission, Beijing, China.

Molavi, J., Barral, D.L., 2016. A Construction Procurement Method to Achieve Sustainability in Modular Construction. Procedia Engineering 145, 1362-1369.
Nadim, W., Goulding, J.S., 2010. Offsite production in the UK: the way forward? A UK construction industry perspective. Construction innovation 10, 181-202.
Pan, W., Gibb, A.G., Dainty, A.R., 2007. Perspectives of UK housebuilders on the use of offsite modern methods of construction. Construction Management and Economics 25, 183-194.
Pan, W., Gibb, A.G., Dainty, A.R., 2012. Strategies for integrating the use of off-site production technologies in house building. Journal of Construction Engineering and Management 138, 1331-1340.
Pan, W., Gibb, A.G., Sellars, A.B., 2008. Maintenance cost implications of utilizing bathroom modules manufactured offsite. Construction Management and Economics 26, 1067-1077.
Pan, W., Sidwell, R., 2011. Demystifying the cost barriers to offsite construction in the UK. Construction Management and Economics 29, 1081-1099.
Polat, G., 2008. Factors affecting the use of precast concrete systems in the United States. Journal of Construction Engineering and Management 134, 169-178.
Poon, C.-s., Yu, T., Ng, L., 2001. A guide for managing and minimizing building and demolition waste. Department of Civil & Structural Engineering, Hong Kong Polytechnic University.
Rogan, A., Lawson, R., Bates-Brkljac, N., 2000. Value and benefits assessment of modular construction. Steel Construction Institute, Ascot, UK.
Schoenborn, J., 2012. A case study approach to identifying the constraints and barriers to design innovation for modular construction. Virginia Tech.
Shen, L., 2008. Constraints for housing industrialization in China Constr Econ 311, 5-8.
Steinhardt, D.A., Manley, K., 2016. Exploring the beliefs of Australian prefabricated house builders. Construction Economics and Building 16, 27-41.
Tam, A., 2007. Advancing the cause of precast construction in Kwai Chung. Hong Kong Engineer 35, 9.
Tam, V.W., Fung, I.W., Sing, M.C., Ogunlana, S.O., 2015. Best practice of prefabrication implementation in the Hong Kong public and private sectors. Journal of Cleaner Production 109, 216-231.
Tam, V.W., Tam, C., Zeng, S., Ng, W.C., 2007. Towards adoption of prefabrication in construction. Building and Environment 42, 3642-3654.
Thanoon, W.A., Peng, L.W., Kadir, M.R.A., Jaafar, M.S., Salit, M.S., 2003. The essential characteristics of industrialised building system, International Conference on Industrialised Building Systems, p. 11.

Wang, J., Li, Z., Tam, V.W., 2014. Critical factors in effective construction waste minimization at the design stage: a Shenzhen case study, China. Resources, Conservation and Recycling 82, 1-7.

Zhai, X., Reed, R., Mills, A., 2014. Factors impeding the offsite production of housing construction in China: an investigation of current practice. Construction Management and Economics 32, 40-52.

Zhang, X., Skitmore, M., 2012. Industrialized housing in China: a coin with two sides. International Journal of Strategic Property Management 16, 143-157.

Zhang, X., Skitmore, M., Peng, Y., 2014. Exploring the challenges to industrialized residential building in China. Habitat International 41, 176-184.

Zhong, R.Y., Peng, Y., Fang, J., Xu, G., Xue, F., Zou, W., Huang, G.Q., 2015. Towards Physical Internet-enabled Prefabricated Housing Construction in Hong Kong. IFAC-PapersOnLine 48, 1079-1086.