BIM-Based Incremental Cost Analysis Method of Prefabricated Buildings in China

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Abstract: In order to achieve the sustainable growth of its urbanization and natural resources, China has been making great efforts to develop prefabricated construction technologies. However, the high incremental cost of prefabricated buildings (PRBs) is a fundamental obstacle to the latter. The current study mainly focuses on analyzing the incremental cost of the on-site construction stage. It is hard to comprehensively identify the incremental cost composition without considering the incremental cost caused by prefabricated components (PFCs) production. Moreover, the results of incremental cost calculation are not accurate enough by comparing the cost of two similar but different PRB and traditional buildings (TRB), and the case-based calculation results suffer from a lack of representation. To address these issues, we first establish a two-dimensional incremental cost index system from the dimension of cost items and prefabricated technologies to study the incremental cost composition of the whole construction stage. Additionally, based on China's latest policies documents, the applicability of incremental cost composition items can also be improved. Then a building information modeling (BIM)-based calculation model is presented to avoid the calculation error caused by comparing the cost of two different PRBs and TRBs. To validate the proposed index system and calculation method, an actual prefabricated project in China is also conducted as a case study. The results suggest that: (1) Incremental cost is composed of band bearing and retaining walls and inner walls PFCs production, PFCs hoisting and grouting, post-pouring concrete, and full decoration. (2) The BIM-based incremental calculation result of a PRB case from Shanghai is within the range of the national average PRB incremental estimation results. The incremental cost composition items and BIM-based calculation approach can greatly help investors to identify the largest increase in cost and make effective cost optimization strategies.

Keywords: prefabricated building; incremental cost; policy documents; BIM

1. Introduction

In recent years, the development of population urbanization in China has been booming. This speeding process of urbanization is undoubtedly associated with higher demand for the improvement of housing conditions and the living environment. By 2020, China's population is expected to reach up to 1.42 billion, and the urbanization rate will increase tremendously from 58.47% to 60.02%, as predicted by the National Health Commission of the People's Republic of China [1,2]. The current construction industry in China cannot meet the fast growing demand for urban housing. Furthermore, the area of completed buildings has continued to decline in recent years, with a year-on-year decline of 11.2% from January to August, 2018 [3]. At the same time, extensive construction methods have also brought material waste such as steel bar, concrete, timber formwork, and resources waste such as water and electricity [4]. Therefore, in order to realize the sustainable development of urbanization and natural resources in China, there is an urgent need for the construction industry to be reformed

with more innovative technologies. Prefabricated construction technology has been introduced and implemented to mitigate these challenges [5,6].

Prefabricated technology is defined as a semi-manufacturing construction method, in which every building component can be freely selected to achieve automated production in factories, and is assembled on site. Due to its unique advantages such as fast construction progress, high quality, and reduced waste of resources, this innovative technology has been highly noticed by the Chinese government and related enterprises. The Ministry of Housing and Urban-Rural Development of the People's Republic of China clearly stated in 2017 that China will strive to increase the proportion of prefabricated building (PRBs) to 30% of the new building area, and increase the number of highly skilled industrial workers to 3 million within 10 years [7]. A great number of leading Chinese real estate enterprises such as Vanke, Country Garden, and China Grand Enterprises have also successively established PRBs and carried out their large-scale construction [8].

Prefabricated technology has been extensively used around China in recent years, however, the implementation of PRBs in various regions of China face the barrier of cost increase [9]. In response to this, the Chinese government has issued incentive policies to deal with incremental cost, such as Beijing's "Implementation Opinions on Accelerating the Development of Prefabricated Buildings" (People's Government General Office, 2018). This document refers to the financial incentives available to firms which prioritize increment cost. These incentives are given to those who opt to construct PRBs and meet implementation standards. However, due to a lack of experience, the industry has not yet figured out in a detailed way the composition of incremental cost index (the incremental cost items relating to the use of assembly construction technology) and quantitative calculation method. Without accurate analysis of incremental cost, it will be difficult for contractors to make profit even if they accept incentive policies and it is also hard for the government to develop and update reasonable standards and regulations for the distribution of subsidies.

2. Brief Literature Review

Many studies have proposed factors that lead to a substantial increase in costs [10,11], such as the technical system not being standardized, the management mode not being uniform, etc. [12]. In order to eliminate those factors, and to accelerate the spread of PRBs, a number of studies have made proposals based on experiences and qualitative analysis method, involving: (1) the intensification of policy support such as financial supports and tax reform; (2) a focus on technological innovation and personnel training; (3) the recruitment of industrial workers to exploit the advantages of reduced labor costs; and (4) the promotion of integrated design, production, and construction, and the strengthening of cooperation between various entities in the industry chain [13,14]. However, although many studies have proposed feasible improvement measures and recommendations, the incremental cost of PRB has not declined [15,16].

To clarify exactly where incremental costs come from, Li et al. [17] used expert interviews and a questionnaire-based survey to study the impact of changes in the value chain on the costs of prefabricated components (PFCs). The results indicated that the market structure of each link in the value chain consists of land costs, pre-development costs, PFC production costs, PFC transportation costs, PFC on-site assembly costs, and running costs. Additionally, Wang et al. [18], conducting statistical analysis, calculated the incremental costs of civil, decorative, and installation projects based on a PRB projects of Shanghai. These studies concluded that the incremental cost of civil projects was the highest [19]. There are many current studies which focus on the calculation method for incremental costs of civil projects at the on-site assembly stage. The methods of comparative analysis and case studies are mainly used for the quantitative calculation of incremental costs. Xiao et al. [20] concluded that the PRB incremental cost is 32 yuan/m^2; they obtained this result by comparing the civil project budget costs of a residential building designed in accordance with the PRB design scheme and traditional design scheme based on bid documents and construction drawing. Furthermore, Wang et al. [21] calculated that the range of PRB incremental cost is between 200 and 500 yuan/m^2.

This conclusion was based on real civil projects costs of 12 pairs of existing PRB and traditional building (TRB) projects with the same structural form, similar building height, and similar construction times. Mao et al. [22] applied the multiple-case study method to conduct an in-depth analysis of the different expenditures involved in using PRB compared to conventional construction methods. Moreover, many numerical models have been deployed to calculate the PRB incremental cost of civil projects. Additionally, Lu et al. [23] proposed an incremental cost data model to predict the incremental costs of civil projects of other PRBs. Their results indicated that PRBs cost 461.41 yuan/m^2 more than TRBs. However, due to the immaturity of PRB development in China, there is a lack of adequate data and case records. This means that many studies must use qualitative analysis methods (i.e., expert interviews) to investigate the incremental costs of PFC production [24].

Given the rapid development of the PRB industry, it is a challenge for researchers to keep pace. The research gaps are caused by insufficient cost data. The PRB cases to be studied are summarized as follows:

- Variables such as building structure and component's positions have a great impact on the accuracy of incremental cost calculation, and there will be a large difference in these variables in two different buildings, so it is hard to guarantee the accuracy of the incremental cost comparison results of two similar but different PFB and TRB. Additionally, there is a large difference (i.e., PFC types, construction location, etc.) in study cases, and the incremental analysis results cannot present the overall situation of the prefabricated industry.

- There is no suitable method to obtain accurate and reliable cost data of the PFC production stage. Therefore, it is hard to quantitatively analyze the whole construction stage incremental cost (including the PFC production and on-site assembly stages).

Building information modeling (BIM) is an engineering data model that integrates various data from engineering projects based on three-dimensional (3D) digital technology [25]. The refined 3D model can be used to correlate the schedule and cost information of the whole construction process by simulation [26,27]. Additionally, the error rate for the cost calculation results can be effectively reduced through automatic calculations, utilizing BIM cost calculation software. In regards to BIM-based construction simulations, Joosung Lee et al. [28]. developed a new BIM-based 4D simulation framework to explore the improved management method for modular construction projects. Based on this new framework, a visually optimal manufacturing process from the three perspectives of resources, material, and quality can be identified and it was also verified that the proposed 4D framework reduces the time and cost needed for module manufacturing. Gulsum Sevde Baltasi et al. [29] demonstrated a pre-construction cost analysis method using BIM and prototype resource integrated planning and simulation software called GSimX, and proved that a BIM-based cost estimation method can help contractors evaluate time and cost results more quickly, more easily and with higher-quality. J L. [30] developed an integrated model that interrelates BIM with construction cost estimation, estimation, scheduling and sustainability at the conceptual design stage of the project to quickly make a reliable construction cost estimate, construction schedule, and preliminary sustainability evaluation for owners and designers.

The objective of this paper is to propose a two-dimensional incremental cost index system. This system is based on the elements of cost items and assembly technologies. The latest authority industry policy documents are used to effectively improve incremental cost composition adaptively and comprehensively in order to avoid the impact associated with the case-studies method on the applicability of the calculation results. Another objective is to propose a BIM-based incremental cost calculation model, in order to rationally transform the same PRB into TRB, which can make it more easy to calculate the incremental stage cost data of the PFC production stage and guarantee the high accuracy of the incremental cost calculation result. The last objective is to validate the accuracy of incremental cost composition items and the calculation approach through a case study from Shanghai.

3. Research Approach

The first objective of this research is to identify the composition of the incremental cost of PRBs. In order to find out the detailed incremental cost index and improve the applicability of the a incremental cost index for all projects in the current PRB industry, this paper used a combination method of fishbone analysis [31] and semi-structured interview methods to propose a two-dimensional incremental cost index system from two dimensions of cost items and assembly technologies. Specifically, the system horizontally identifies each cost item based on the "PRB project consumption quota (TY01-01(01)-2016)" (CQ), while vertically analyzing the incremental cost of each assembly technology used, based on the "PRB Evaluation Criterion (GB/T51129-2017)" (EC). The kinds of cost items and assembly technologies showed in CQ and EC are based on the statistical information of all existing PRB projects around China. The fact that incremental cost analysis results can be better applied to different PRBs is the key reason for introducing CQ and EC.

The second objective was to develop a quantitative incremental cost calculation method of the total construction stage. To avoid the research gap of insufficient cost data of the PFC production stage and the incorrect cost data of manual calculation, 3D BIM model and cost simulation for the entire construction process (from production of prefabricated parts to main decoration) were applied.

As the cost difference between PRBs and TRBs mainly emerge at the construction stage [32], this paper targets the incremental costs of the construction process. Thus, in order to simplify the complicated study process, a research framework was established, as shown in Figure 1.
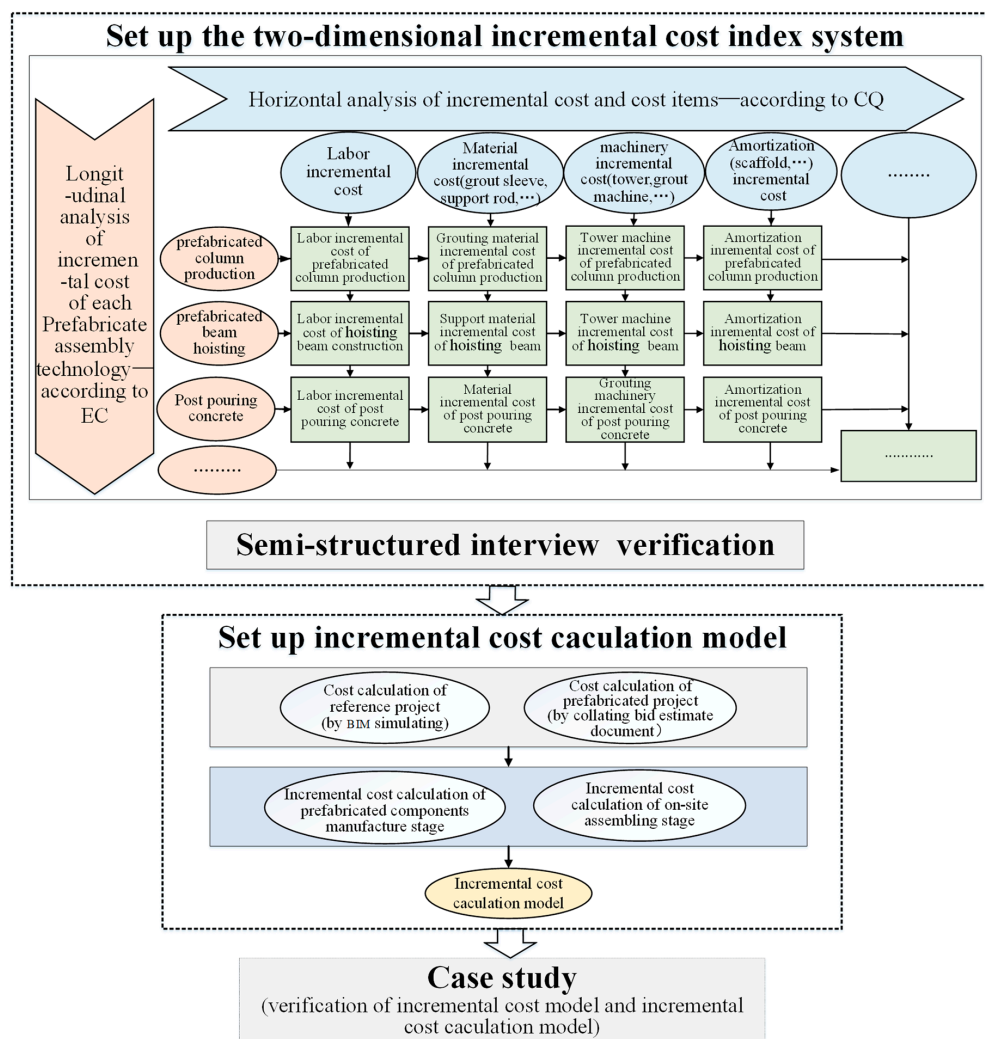

Figure 1. Research framework of PRB incremental cost.

3.1. Two-Dimensional Incremental Cost Index System

The concept of incremental cost is developed from the concept of marginal cost [33]; it refers to the cost incurred due to the implementation of a specific plan. If a plan is not adopted, there will be no incremental cost. This is the definition method of the incremental cost method for green building, which is relatively mature [34–37]. This study defines the incremental cost of PRBs as the increased costs (the decreased costs are also recorded as incremental cost, with the symbol marked as negative) due to the selection of the assembly technology, according to the requirements of the CQ and EC. It includes direct incremental cost items (labor, materials, and machinery), and measures incremental cost items (template amortization, etc.), indirect incremental cost items (fees, overheads), tax and profit.

3.1.1. Identification of PRBs Incremental Cost Items

As there are fundamental differences between the structural forms and construction technologies of PRBs and TRBs, there will be large differences in the composition of cost items when they are transformed, using the traditional construction method, into assembly technology [38]. QC was prepared by Ministry of Housing and Urban- Rural Development of the People's Republic of China (MOHURD). It is based on the cost data statistical analysis results of every PRBs case across China and has been in use since March 2017. QC is an authoritative PRB calculation standard incorporating all kinds of PRB construction cost items related to unique PRB features and new assembly technologies (i.e., factory automatic manufacture, hoisting and grouting of PFCs and integrated decoration). In order to comprehensively identify incremental cost items, this study uses the fishbone analysis method to distinguish different cost items compared with the TRBs, according to QC. A fishbone analysis diagram of incremental cost items of PRBs was compiled from the four aspects of direct costs, indirect costs, measure costs, and profit and tax in Figure 2. In the figure, the cost items in italic subscript result from the adoption of assembly technology.
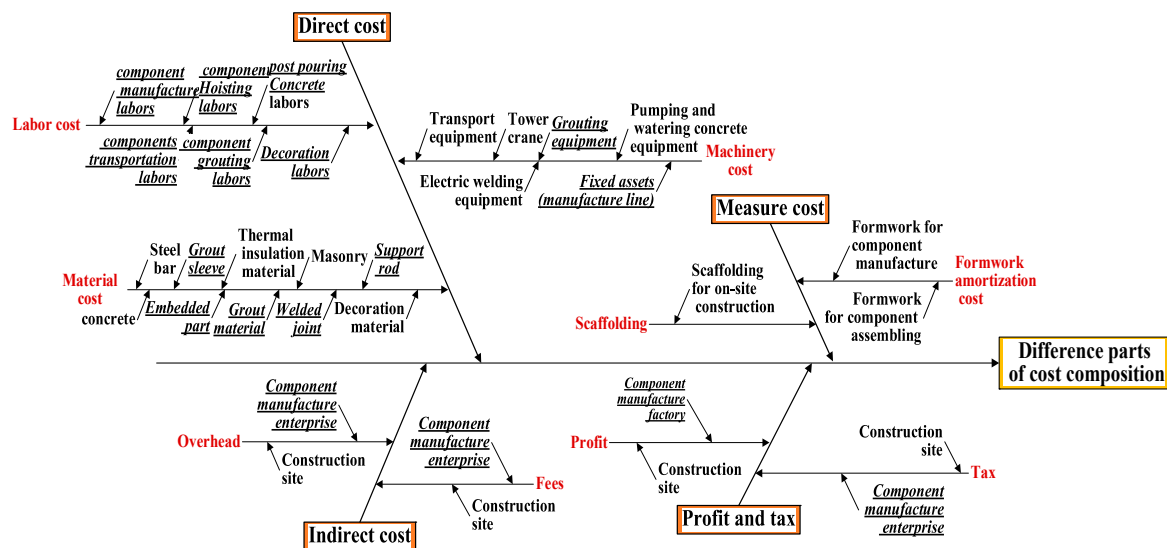

Figure 2. Fish bone analysis diagram of PRBs incremental cost items.

3.1.2. Classification of PRBs Incremental Cost Items

EQ is the only existing PRBs evaluation criterion. Prepared by MOHURD and in use since February, 2018, it is applicable to all PRBs in China. EQ was introduced to evaluate the degree of prefabrication of PRBs (the comprehensive ratio of prefabricated parts used in the main structure, the retaining wall, the inner partition wall, the decoration and the equipment pipeline above the outdoor floor [39]). The evaluation criteria are based on two aspects of PFC types and assembly technologies. All PRBs must be designed to meet the requirements of EQ. Evaluation scores are the

basis for applications to receive policy subsidies. To render the calculation of the incremental cost of assembly technologies more scientifically, this study uses the cross classification method [40] to analyze incremental cost distributions for each assembly technology in the EQ (all incremental cost items are presented in Figure 2); these are then separated from the construction time dimension of PFCs production and on-site assembly construction stages, such as the material incremental cost of producing PFCs, which consist of concrete, rebar and grouting sleeves. In order to analyze the incremental cost for the whole PRB construction in greater depth and to make the method easier to use, this paper takes the EQ assembly technologies as its first-level index, and the incremental cost items of the PFCs production and on-site assembly construction stages as its secondary index. This was performed to generate the two-dimensional incremental index system, as shown in Table 1.

Table 1. Assembly technology incremental cost, and preliminary construction of two-dimensional index system.

Assembly Technologies (First-Level Indicators)		Incremental Cost Distribution and Classification	
		PFCs Production Stage (Second-Level Indicators)	On-Site Assembly Construction Stage (Second-Level Indicators)
Load-bearing structural components construction (automatically factory product,	Columns, load-bearing walls, ductile wall panels, etc. vertical load-bearing components	Labor cost: labor cost for structural components production Material cost: rebar, concrete, grout sleeves, insulation parts for bearing structural components production Machinery cost: fixed asset, manufacture line Measure cost: formwork amortization Other costs: overheads, taxes, transportation fee	Labor cost: bearing structural components hoisting, grouting and post-concrete pouring labor Material cost: bearing structural components supporting rods, grouting material, rebar, concrete Machinery cost: grouting machinery, tower crane Measure cost: formwork, scaffold Other cost: overheads, taxes, profit
	Beams, slabs, stairs, balconies, air conditioning panels and other cover members		
Non-load-bearing components	Outer maintenance components	Labor cost: Non-load-bearing components construction labor Material cost: rebar, concrete, grout sleeves, insulation parts for non-load-bearing components construction Machinery cost: fixed asset, manufacture line Measure cost: formwork amortization; other costs: overheads, taxes, transportation fees	Labor cost: Non-load-bearing components hoisting, grouting and post-concrete pouring labor Material cost: Non-load-bearing components supporting rods, grouting material, rebar, concrete Machinery cost: grouting machinery, tower crane Measure cost: formwork, scaffold Other cost: overheads, taxes, profit
	Internal wall		
Decoration	Full decoration	——	Labor, material, machinery costs for floor, baseboard, wall roof and ceiling decoration

3.1.3. Verification and Correction of Two-Dimensional Incremental Index System

Although this two-dimensional incremental index system has been developed using scientific research methods and with reference to authoritative policy documents, since QC and EQ have only recently been implemented, it is a challenge to verify their accuracy in practice [41]. The expert interview method is a more reliable and convenient means to obtain reliable PRBs incremental cost information and is thus adopted here. This study used research experts in the field of industrial construction who spoke with personnel from leading PRB companies [42]. The latter were from the leading companies, including PFC manufacturing managers, PRB projects cost managers and EPC developers. This study included experts in the fields of engineering projects management, new industrial building, information construction technology, etc. The name, title and workplace information of each expert is shown in Table 2. In the interviews, researchers queried the accuracy of each incremental cost index item and the rationality of the index classification. Their objectives were to collect data on the actual conditions of nine prefabricated projects, utilizing their research experience, and to complete of the incremental cost index questionnaire.

Table 2. The name, title, and workplace information of each experts.

Letter ID	Title	Workplace
A	Dean, School of Civil Engineering	North China University of Technology (Beijing, China)
B	Deputy Head of the School of Civil Engineering	North China University of Technology
C	Assistant/professor of the construction economic evaluation	North China University of Technology
D	Lecturer at the School of Smart Construction	North China University of Technology
E	Lecturer in project management	North China University of Technology
F	Executive vice president (real estate)	Longxin Construction Group Co., Ltd. (Nantong, China)
G	Professor-level senior engineer	Zhongjian City Construction Development Co., Ltd. (Beijing, China)
H	Director of Intelligent Director of the Intelligent Manufacturing Department	Sanyi Group Co., Ltd. (Beijing, China)
I	Senior Engineer	China Construction First Bureau Group Co., Ltd. (Beijing, China)
J	Researcher-level Engineer	Nantong Architectural Design and Research Institute Co., Ltd. (Nantong, China)
K	Senior engineer	Haimen City Construction Drawing Review Center (Haimen, China)
L	Senior engineer	Shanghai Zhongsen Building & Engineering Design Consultant Co., Ltd. (Shanghai, China)
M	Assistant/Professor of the project evaluation	Tongji University (Shanghai, China)
N	Chief Engineer	Shenyang Wanrong Modern Construction Industry Co., Ltd. (Shenyang, China)
O	Lecturer of project economic management	Harbin Institute of Technology (Harbin, China)

Each incremental cost item in the index system has a higher frequency in actual projects, with more than 95% of incremental index items appearing seven times or more in nine actual prefabricated projects. The latter figures were obtained through the summary and analysis of interview results (the interview data analysis process is shown in Figure 3), thus further verifying the initial two-dimensional incremental cost index system. However, due to lack of practical experience, 15 experts advised that the material incremental cost items should be supplemented with embedded parts, thermal insulation, and masonry. Machinery increments needed to be supplemented with welding equipment and concrete vibrators.

In order to reduce the complexity of the index system and increase the availability of incremental cost data, the indicators hierarchy is divided and revised in accordance with the sequence of construction stages—assembly construction technology—incremental expense types, while five indicators of embedded parts were added on the basis of the original. The final two-dimensional incremental cost index system is shown in Figure 4.

expert incremental cost index items		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Load-bearing structural components production	labor	9	9	9	9	9	8	9	9	8	9	9	7	9	9	9
	rebar	9	8	9	9	6	8	9	9	7	9	9	9	9	8	9
	concrete	9	9	9	9	9	8	9	9	8	9	9	7	9	9	9
	grout sleeves	9	7	8	8	9	9	8	9	6	7	8	6	8	7	7
	insulation parts	9	9	9	9	9	8	9	9	8	9	8	7	9	9	9
	fixed asset	9	9	9	9	9	8	9	9	8	9	9	7	9	9	9
	manufacture line	8	9	9	9	9	8	9	9	8	9	8	7	9	9	7
	formwork amortization	9	9	9	9	9	8	8	9	8	9	9	7	9	9	9
	overheads	9	9	9	9	9	8	9	9	8	9	7	9	9	9	9
	taxes	9	9	8	9	9	8	9	9	8	9	9	8	9	9	9
	transportation fee	9	9	8	9	9	8	9	9	8	9	9	8	9	9	9
Non-load-bearing components production	labor	9	9	8	9	9	8	9	9	8	9	8	8	9	9	9
	rebar	9	9	9	9	9	8	9	9	8	9	9	8	9	9	9
	concrete	9	9	9	9	9	8	9	9	8	9	9	8	9	9	9
	grout sleeves	9	9	9	9	9	8	7	9	8	9	9	8	9	9	9
	insulation parts	9	9	9	9	9	8	8	9	8	9	9	7	9	9	9
	fixed asset	9	9	9	9	9	8	9	9	8	9	9	7	9	9	9
	manufacture line	9	9	9	9	9	8	9	9	8	9	9	6	9	9	9
	formwork amortization	9	9	9	9	9	8	9	9	8	9	9	7	9	9	8
	overheads	9	9	9	9	9	8	9	9	8	9	8	9	9	9	9
	taxes	9	9	9	9	9	8	9	9	8	9	8	9	9	9	9
	transportation fee	9	9	9	9	9	8	9	9	8	9	9	9	9	9	9
Load-bearing structural components on-site construction	labor	7	7	8	8	9	9	8	9	6	7	9	9	8	7	7
	supporting rods	7	9	9	9	7	8	9	9	8	9	9	9	9	9	9
	grouting material	7	9	9	9	9	8	9	9	8	9	9	9	9	9	9
	rebar	9	9	9	9	9	8	9	9	8	9	9	7	9	9	9
	concrete	9	9	9	9	9	8	8	9	7	9	9	9	9	9	9
	grouting machinery	9	9	9	9	9	8	9	9	8	9	9	7	9	9	9
	tower crane	9	9	9	9	9	8	9	9	8	9	9	7	9	9	9
	formwork	9	9	9	9	9	8	9	9	8	9	9	9	9	9	9
	scaffold	9	9	9	9	9	8	9	9	8	9	7	9	9	9	9
	overheads	8	9	9	9	9	8	9	9	7	9	9	9	9	9	9
	taxes	9	9	9	9	9	8	9	9	8	9	7	7	9	9	9
	profit	9	9	9	9	9	8	9	9	8	9	7	8	9	9	9
Non-load-bearing component on-site construction	labor	9	7	8	8	9	9	8	9	6	7	8	8	8	7	7
	supporting rods	8	9	9	9	9	8	9	9	8	9	9	8	9	9	9
	grouting material	9	9	9	9	9	8	9	9	8	9	9	8	9	9	9
	rebar	9	9	9	9	9	8	9	9	8	9	9	8	9	9	9
	concrete	9	9	9	9	9	8	9	9	8	9	9	8	9	9	9
	grouting machinery	9	9	9	9	9	8	9	9	8	9	9	8	9	9	9
	tower crane	9	9	9	9	9	8	6	9	8	9	9	8	9	9	9
	formwork	9	9	9	9	9	8	9	9	8	9	9	8	9	9	9
	scaffold	8	9	9	9	9	8	9	9	8	9	9	9	9	9	9
	overheads	9	9	9	9	9	8	9	9	8	9	9	9	9	9	9
	taxes	9	9	9	9	9	8	9	9	7	9	9	9	9	9	9
	profit	9	9	9	9	9	8	9	9	8	9	9	9	9	9	9
Full decoration of floor, baseboard, wall roof and ceiling decoration	Labor	9	7	8	8	9	9	9	9	6	7	9	9	8	7	7
	material	9	9	9	9	9	8	9	9	8	9	9	8	9	9	9
	machinery	7	9	9	9	9	8	9	9	8	9	9	7	9	9	9
Supplementary	embedded parts	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	thermal insulation	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	masonry	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	welding equipment	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	concrete vibrators	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Figure 3. Interview data collation. A–O represent the experts mentioned in Table 2. The numbers shown in this figure represent the number of occurrences of each incremental cost index items in nine PRB projects. ○ represents the supplementary items which appear seven times or more in nine PRB projects.
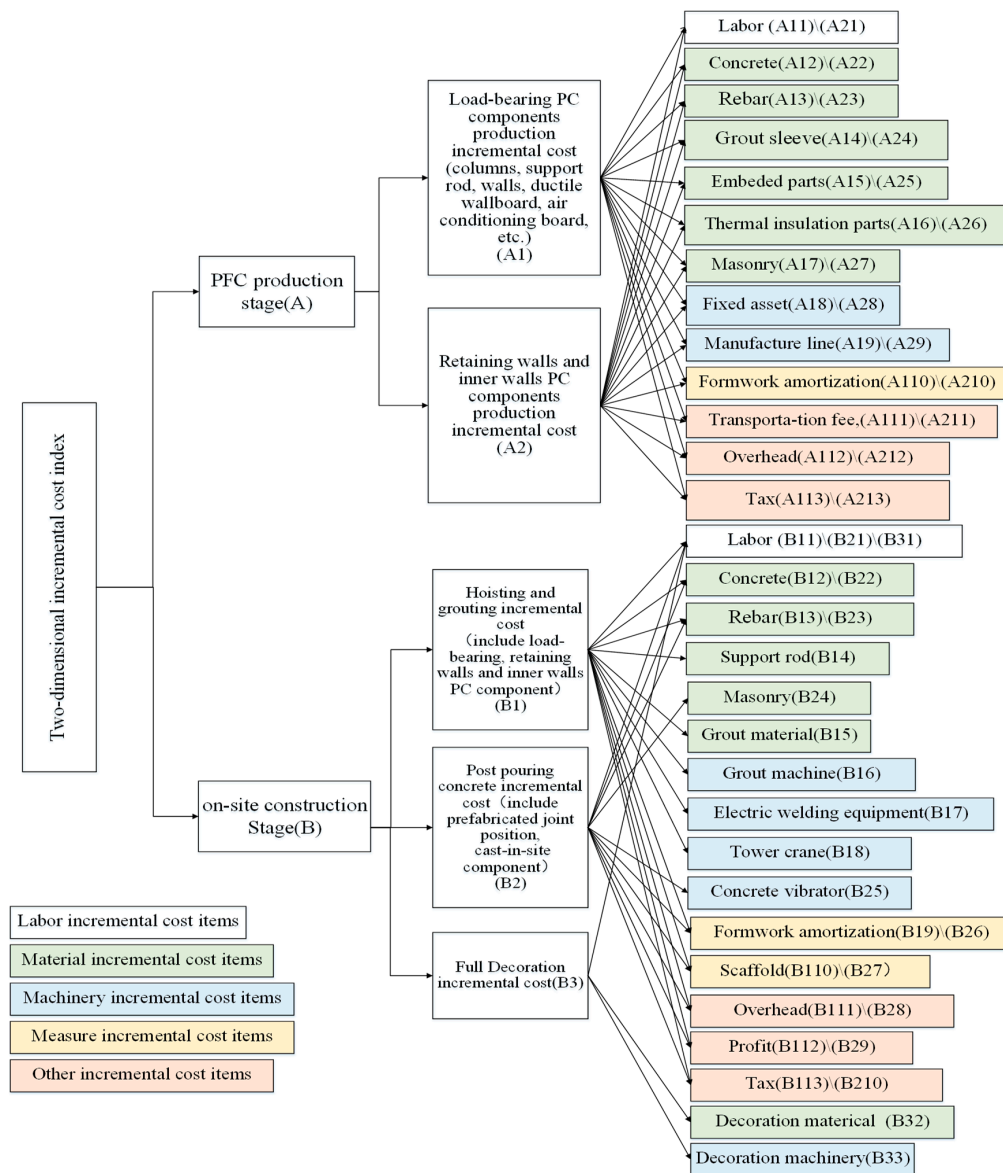
Figure 4. The two-dimensional incremental cost index system.

3.2. Incremental Calculation Model Based on BIM Simulation

Before calculation, it is necessary to clarify the method of calculation for the reference and the prefabricated projects. Additionally, the calculation of engineering quantities and the selection of integrated unit prices needs to be attended to, as these are key indicators of the accuracy of the calculation results [43]. The cost calculation model is therefore proposed on the basis of the following principles: (1) accurate calculation of engineering quantities of the reference and the prefabricated projects; (2) detailed setting engineering quota for the two different projects.

3.2.1. Cost Calculation for Reference Project

The cost of simulation of the traditional construction is taken as the cost of the reference project. The degree of accuracy to be obtained by BIM models determines the accuracy of engineering quantities and the cost calculation. Common BIM modeling software includes Revit, Bentley and Mechanical. The building information modeling established by Revit has the following advantages over other BIM software: (1) the model accuracy can reach LOD400 (the evaluation standard of building models); (2) it interfaces with calculation software such as Luban and Glodon. Additionally, engineering

quantity calculation accuracy is obtainable to within ±10% of acceptable deviation [44]. This study uses prefabricated exterior wall components from the case study to illustrate the evolution of Revit modeling accuracy (see Figure 5).
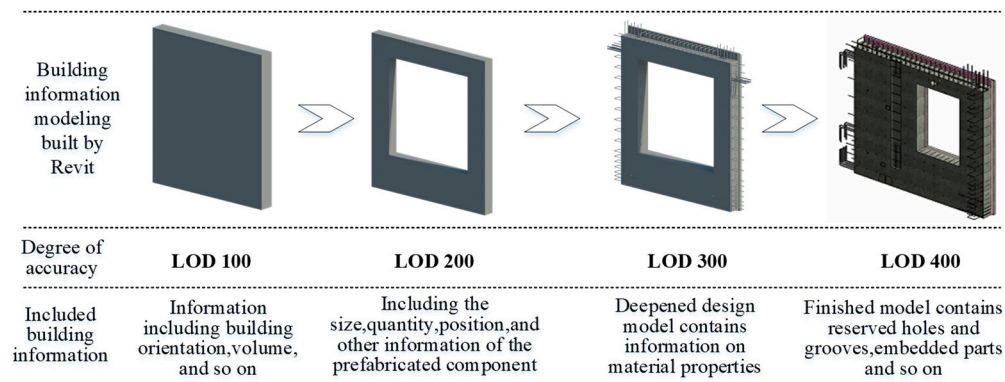

Figure 5. Degree of accuracy of the evolution process of building construction models by Revit.

Common BIM calculation and cost calculation software includes Glodon, Luban, and Tsinghua Sware. Among them, Luban software and Revit are both developed on the AutoCAD platform and the strong compatibility can greatly reduce the accuracy error caused by Revit model import. For example, some frame columns will be identified as concealed columns when the Revit model is imported into Glodon due to the poor compatibility, and a large engineering calculation error will be produced because the calculation rules of frame columns and concealed columns are quite different. Moreover, with the strong compatibility, the buildings models can be bi-directionally imported between Luban software and Revit, software which can greatly improve the efficiency of model modification. This paper refines a Revit building model and calculates the engineering quantity and cost using Luban Architecture and Luban Estimator. It takes the calculation results to be the reference project cost. The calculation process is shown in Figure 6.
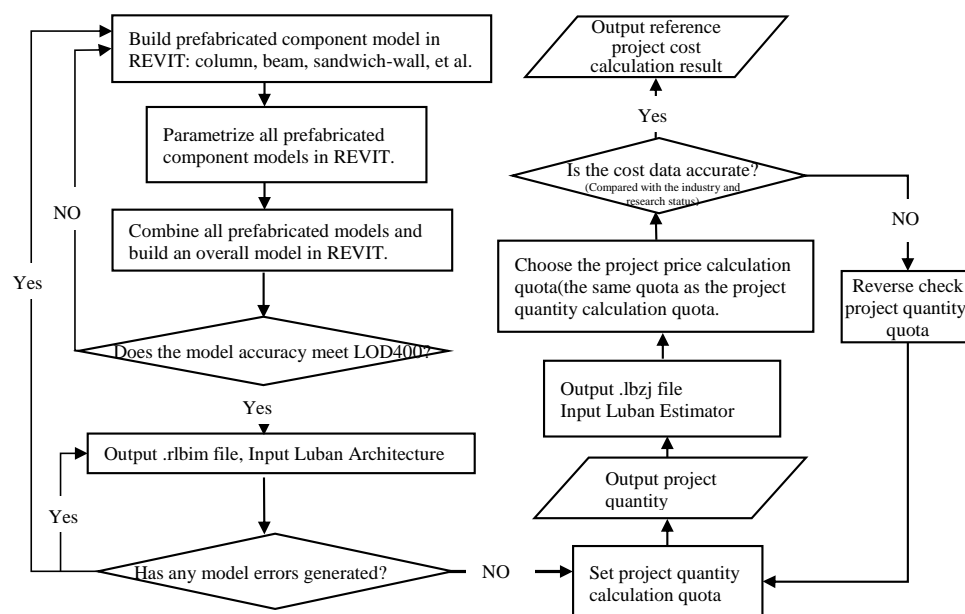

Figure 6. The calculation process of reference project cost.

3.2.2. Cost Calculation for Prefabricated Project

The process of constructing PRBs has five stages. The engineering cost documents for each stage are shown in Figure 7. Among them, the bid estimate document was more accurate than other cost documents before construction [45]. This study therefore takes the PRBs contract cost documents obtained from investigation and research to be the cost of the prefabrication project and compares this to the reference project cost.
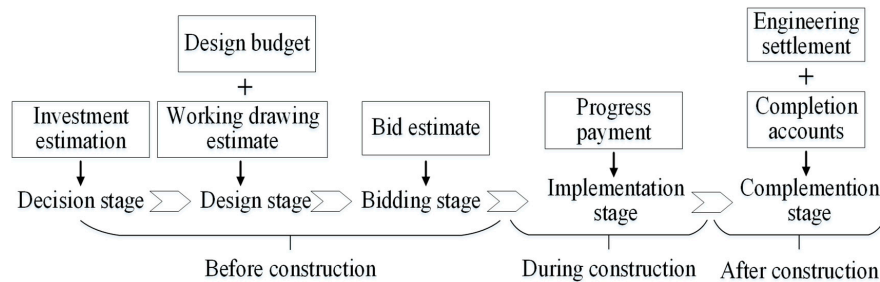

Figure 7. Cost documents in the whole construction stage by type.

3.2.3. Incremental Cost Calculation Model

The construction stage incremental cost is the sum of the PFC production stage incremental cost and the on-site construction stage incremental cost. The PFC production incremental cost is equal to the difference between the PFCs production cost of the assembly construction method and the traditional construction method. The on-site construction stage incremental cost is equal to the sum of the hoisting, post-pouring concrete, and full decoration incremental cost. The BIM-based incremental cost calculation model is shown in Figure 8; the calculation formula is shown in Table 3.
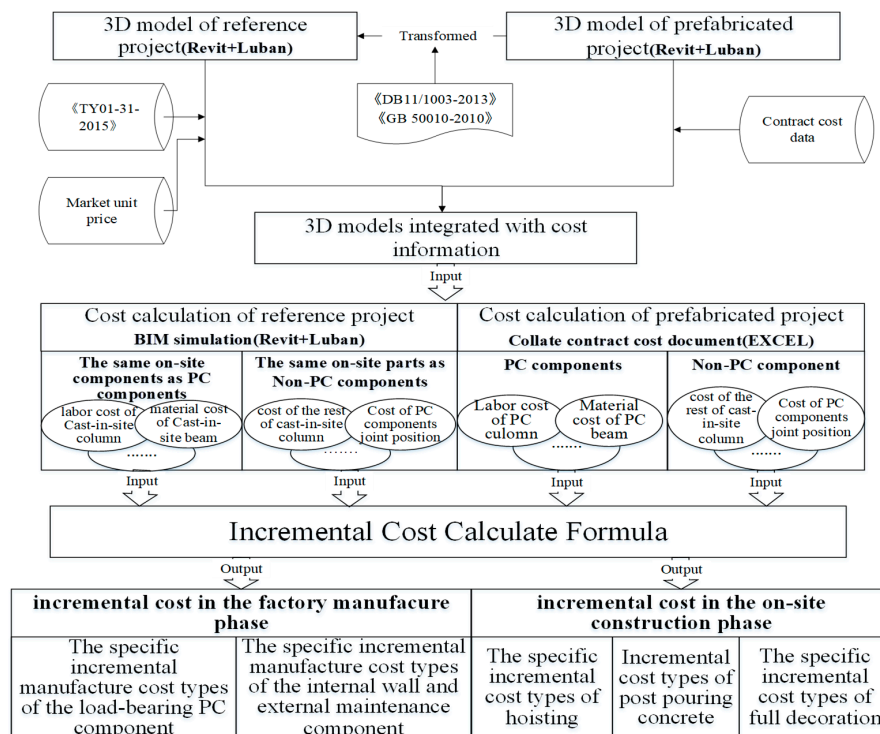

Figure 8. BIM-based incremental cost calculate model. <DB11/1003-2013>, <GB 50010-2010>, <TY01-31-2015> represent Design Specification for Precast Concrete Shear Wall Structure, Code for design of concrete structures and Consumption quota of housing construction and decoration engineering, respectively, which were published by MOHURD. The market unit price represents the average price of building materials of TRB, which was counted by local government departments.

Table 3. Incremental calculation model based on BIM simulation.

	Formula	Symbolic Interpretation
Factory manufacture stage Load-bearing PC components incremental cost (1)	$\Delta C_L = \sum\limits_{i=1,j=1}^{4,6} \left(C_{Pij} - C_{Tij} \right)$	C_{Pij}-prefabrication of the *i*-th load-bearing PC component, *j*-th cost C_{Tij}-simulation of on-site pouring the *i*-th load-bearing PC component, *j*-th cost
Factory manufacture stage Internal wall and outer maintenance PC components incremental cost (2)	$\Delta C_M = \sum\limits_{k=1,j=1}^{2,6} \left(C_{Pkj} - C_{Tkj} \right)$	C_{Pkj}-prefabrication of the *k*-th non-load-bearing PFC, *j*-th cost C_{Tkj}-simulation of on-site pouring the *k*-th Non-load-bearing PFC, *j*-th cost
Factory manufacture stage incremental cost (3)	$\Delta C_H = \Delta C_L + \Delta C_M$	ΔC_L: load-bearing PFC incremental cost ΔC_M: non-load-bearing PFC incremental cost
On-site construction stage-hoisting incremental cost (4)	$\Delta C_E = \sum\limits_{g=1}^{5} (C_{Pg} - C_{Tg})$	C_{Pg}: *g*-th hoisting cost of prefabricated construction C_{Tg}: *g*-th hoisting cost of traditional construction
On-site construction stage-Post-concrete pouring incremental cost (5)	$\Delta C_T = \sum\limits_{t=1}^{5} (C_{Pt} - C_{Tt})$	C_{Pt}: *s*-th full decoration cost of prefabricated construction. C_{Tt}: *t*-th post-concrete pouring cost of traditional construction
On-site construction stage-Full decoration incremental cost (6)	$\Delta C_S = \sum\limits_{s=1}^{5} (C_{Ps} - C_{Ts})$	C_{Ps}: *s*-th full decoration cost of prefabricated construction C_{Ts}: *s*-th full decoration cost of traditional construction
On-site construction stage incremental cost (7)	$\Delta C_J = \Delta C_E + \Delta C_T + \Delta C_S$	ΔC_E: incremental cost of hoisting ΔC_T: incremental cost of post-concrete pouring ΔC_S: incremental cost of full decoration
Total incremental cost (8)	$\Delta C = \Delta C_H + \Delta C_J$	ΔC_H: factory manufacture stage incremental cost ΔC_J: on-site construction stage incremental cost

Note: (1) The *i*-th load-bearing PC components include laminated floors, stairs, balconies, sandwich walls, beams, and columns; (2) the *k*-th Non- load-bearing PC components include internal partitions, prefabricated floor (PCF) panels, and equipment platform boards; (3) post-concrete pouring cost includes the concrete pouring cost of PFCs connection joints and remaining non-PC components cost (cast-in-place beams, cast-in-place columns); (4) the *j*-th cost items include labor cost, material cost, machinery cost, transportation cost, measure cost, and indirect cost; (5) the *j*-th cost is the product of the engineering quantity and the integrated unit price for each type of expense; (6) simulated on-site pouring concrete cost is obtained from BIM software output and prefabricated construction cost is from corporate contract cost documents.

4. Case Study

4.1. Brief Introduction to the Demonstration Project

The demonstration project is located in Qingpu District, Shanghai, China. It is a commercial housing project with residences, property management and other supporting services. The building type is an assembled integral shear wall structure. The total ground area is 4015 m². The main load-bearing PFCs are prefabricated laminated panels, prefabricated stairs, prefabricated balconies, and prefabricated exterior walls. Non-load-bearing PFC includes prefabricated interior walls and PCF panels. The distribution of PFCs is shown in Figure 9. The overall PC degree is 46.34%, while the standard assembly has 3–8 layers. This prefabricated project is therefore very representative. The PFC production factory is located in Haimen City, Jiangsu, China. It has an automated manufacturing line with mold installation stations, concrete installation and vibration stations, steaming stations, etc., and is located about 240 km from the construction site. The reference project cost is calculated assuming a 17% VAT taxation method and taking the local market comprehensive unit price as the labor, materials, and machinery cost calculation of comprehensive unit price. For the reference project, engineering quantity and cost calculation quota, the "Shanghai 2000 Municipal Building and Decoration Project Budget Quota" was used.
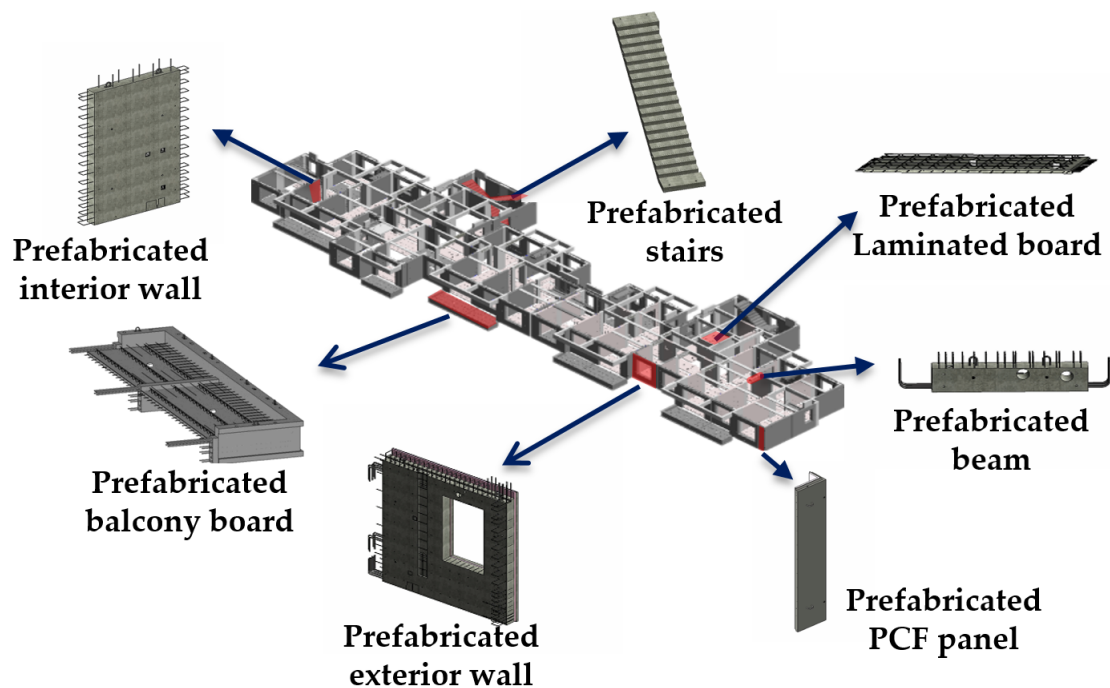
Figure 9. Prefabricated component distribution of the demonstration project standard floor.

4.2. Incremental Calculation Results of the Whole Construction Period

The incremental calculation formula proposed in Table 3 was used to calculate the incremental cost index proposed in Figure 4. The cost of the reference project was calculated by BIM simulation. The cost of the prefabrication project was obtained from the PRB construction enterprise and the PFC production factory. Based on the incremental cost index from Figure 4 (A11–A110, A21–A210, B11–B113, B21–B210, B32–B33) and Equation (8) in Table 3, the data sources of prefabricated construction and reference construction cost are shown in Table 4, and the whole construction incremental cost was first calculated to perform an overall analysis, as shown in Table 5. For detailed analysis, the sources of incremental cost, incremental cost of the PFC production stage and on-site construction stage were respectively calculated based on A11–A113 and A21–A213 in Figure 4, and Formulas (1) and (2) in Table 3, as shown in Tables 6–9.

Table 4. Type and source of incremental for the whole construction stage.

Index	Corporate Cost Document (Prefabricated Construction Cost)	BIM Simulation (Reference Construction Cost)
Incremental cost of bearing and non-load-bearing PFC production	PFC design drawings PFC manufacture plan PFC cost contract (From components manufacturers)	PFC model(Revit) types; PFC engineering quantity types; (Luban Architecture); Manufacture cost of each type of PFC (Luban Estimator)
Incremental cost of bearing and non-load-bearing PFC hoisting	Structural design drawings Architectural design drawings Construction organization design On-site construction cost documents (from EPC contractor)	Whole building and each type of PFC model (Revit); Engineering quantity of post-concrete pouring parts, decoration and each type of PFC (Luban Architecture); On-site construction cost of post-concrete pouring parts, decoration and each type of PFC (Luban Estimator)

Table 5. Total incremental cost of the whole construction stage. The cost items refer to the incremental cost index proposed in Figure 4. Labor cost items are A11, A21, B11, B21, and B21. Material cost items are A12–A17, A22–A27, B12–B15, B22–B24, B32. Machinery cost items are A18, A19, A28, A29, B16–B18, B25, and B33. Measurement cost items are A110, A210, B19, B26, B110, and B27. Transportation, indirect, profit and tax cost items respectively refer to A111–A113, A211–A213, B111–B113, and B28–B210. The results are calculated using Equation (8) (proposed in Table 3) (yuan/m^2).

Cost Items	Construction Stage	Labor	Material	Machinery	Measure	Transportation	Indirect	Profit and Tax	Total
	PFC production	−85.15	81.26	97.59	167.09	58.95	53.81	107.28	480.82
On-site construction	Hoisting and grouting	−48.90	132.52	133.85	——	——	−25.63	2.79	194.61
	Post-concrete pouring	−2.01	−5.89	−1.67	−3.34	——	−1.12	−1.18	−15.22
	Full decorati-on	−2.62	−2.13	−0.91	——	——	——	——	−5.67
Total		−138.69	205.77	228.86	163.74	58.95	27.05	108.89	654.58

Table 6. Incremental cost of the prefabricated PFC production stage. The cost items refer to the incremental cost index proposed in Figure 4. The results of load-bearing PFCs are calculated using indicators A11–A113 and Equation (1) (proposed in Table 3) (yuan/m^2). The results of internal wall and outer maintenance PFCs are calculated using indicators A21–A213 and Equation (2) (proposed in Table 3) (yuan/m^2).

Cost Items	PFC Types	Load-Bearing PFCs				Internal Wall and Outer Maintenance PFCs		Total
		Laminated Floor	Stairs	Balcony	Sandwich Wall	Internal Wall	PCF Panel	
	Labor	−192.348	−64.71	−172.72	−138.58	−29.12	−147.279	−744.76
Material	Steer bar	115.1854725	13.17	10.06	15.60	15.30	15.25	184.57
	Concrete	119.80	14.52	52.64	15.21	45.25	15.27	262.69
	Grouting sleeve	—	—	—	84.99	170.81	—	255.80
	Embedded parts	39.59	59.41	35.48	56.22	62.10	80.12	332.92
	Insulation material	—	—	—	12.92	—	22.04	34.96
	Masonry	—	—	—	−35.95	−324.22	—	−360.172
Formwork amortization		153.46175	184.95	369.18	300.01	252.02	201.74	1461.36
Machinery		51.98	113.15	297.67	142.52	154.99	93.19	853.5
Transportation		47.50	91.74	72.20	90.21	94.45	119.50	515.6
Overhead		66.75	68.96	67.44	83.87	74.09	109.55	470.66
Tax		94.88	171.82	201.04	179.64	187.60	103.37	938.36
Total		496.79	653.02	932.99	806.72	703.25	612.76	4205.53

Table 7. Incremental cost of on-site assembling stage-hoisting. The cost items refer to the incremental cost index proposed in Figure 4. The results of load-bearing PFCs are calculated using indicators A11–A113 and Equation (4) (proposed in Table 3) (yuan/m^3). The results of internal wall and outer maintenance PFCs are calculated using indicators A21–A213 and Equation (4) (proposed in Table 3) (yuan/m^3).

Cost Items	PFC Types	Load-Bearing PFCs				Internal Wall and Outer Maintenance PFCs		Total
		laminated Floor	Stair	Balcony	Sandwich Wall	Internal Wall	PCF Panel	
	Labor	−90.40	−79.23	−64.08	−67.36	−65.63	−61.04	−427.74
Material	Support rod	165.76	129.19	211.48	216.61	214.28	168.28	925.60
	Grouting material	—	—	—	114.33	119.16	—	233.49
Machinery	Grouting Machinery	—	—	—	29.70	49.35	—	79.05
	Welding equipment	37.17	—	30.74	—	—	—	67.91
	Tower crane	101.54	172.19	239.59	131.27	109.45	89.68	1023.72
Overhead		−26.06	−29.06	−37.47	−53.99	−61.01	−16.62	−224.21
Profit		−23.56	−20.04	−29.66	−50.97	−75.87	−22.84	−222.94
Tax		27.96	29.42	59.60	54.33	49.25	26.77	247.33
Total		192.41	202.47	410.20	373.92	338.98	184.23	1702.21

Table 8. On-site assembly construction stage incremental cost post-concrete pouring. The results of assembly construction are calculated using the incremental cost index proposed in Figure 4 (B11–B1113, B21–B210) and Formula (5) (proposed in Table 3) (yuan/m^2).

Cost Items	Construction Method	Assembly Construction	Traditional Construction	Total
Labor		63.15	65.17	−2.01
Material	Rebar	106.56	107.72	−1.17
	Concrete	101.41	102.67	−1.26
	Masonry	89.31	90.68	−1.38
	Straight thread Connector	0.95	2.10	−1.05
	Electro slag pressure welding head	11.11	12.13	−1.02
Machinery	Concrete vibrator	8.72	10.39	−1.67
Measure cost	Formwork amortization	177.87	179.41	−1.54
	Scaffold amortization	33.36	35.168	−1.81
	Fees	136.86	173.98	−1.12
	Tax	99.26	100.44	−1.76
	Total	828.53	843.75	−15.22

Table 9. On-site assembly construction stage incremental full-cost decoration. The results are calculated using indicators proposed in Figure 4 (B31, B32, B33) and Equation (6) (proposed in Table 3) (yuan/m^2).

Cost Items	Construction Method	Assembly Construction	Traditional Construction	Total
Labor	Floor decoration	12.81	13.37	−0.56
	Wall decoration	70.57	71.25	−0.69
	Ceiling decoration	3.10	3.55	−0.45
	Baseboard decoration	0.21	0.63	−0.42
	Roof decoration	7.50	8.01	−0.51
Material and machinery	Floor decoration	21.28	21.91	−0.63
	Wall decoration	35.63	36.55	−0.92
	Ceiling decoration	1.92	2.43	−0.51
	Baseboard decoration	0.07	0.50	−0.43
	Roof decoration	16.76	17.32	−0.55
	Total	169.85	175.51	−5.66

4.3. Incremental Cost Calculation Results Analysis

4.3.1. Incremental Cost Analysis of the Whole Construction Stage

Overall, the PRB construction cost is 654.58 yuan/m^2 higher than for TRBs. The cost of post-concrete pouring technology and full decoration technology cost are the reduction costs. The costs of PFC production and grouting and hoisting technology increased, among which, the PFC production cost increased the most. The proportion of incremental cost and cost item in the whole construction stage s is shown in Figure 10.

Figure 9 shows that the machinery incremental cost for the entire construction process is 228.86 yuan/m^2. This accounts for 35%. The incremental cost of materials, measurements, and profits and taxes are 205.76, 163.74 and 108.89 yuan/m^2, respectively, which account for 31.4%, 25% and 16.6% respectively. The labor cost is decremented: −138.69 yuan/m^2.

The machinery incremental cost consists of manufacture line, tower cranes for hoisting, and grouting costs. China is in the early stages of its development of PRB, so PFC production and construction enterprises still face many challenges, such as the large initial investment required and the lack of familiarity with installation technologies needed at construction sites. Furthermore, given the increase in the number of PC component orders, the industry must also confront obstacles to the improvement of assembly construction technology, the depreciation of manufacturing lines and tower cranes and other incremental costs.
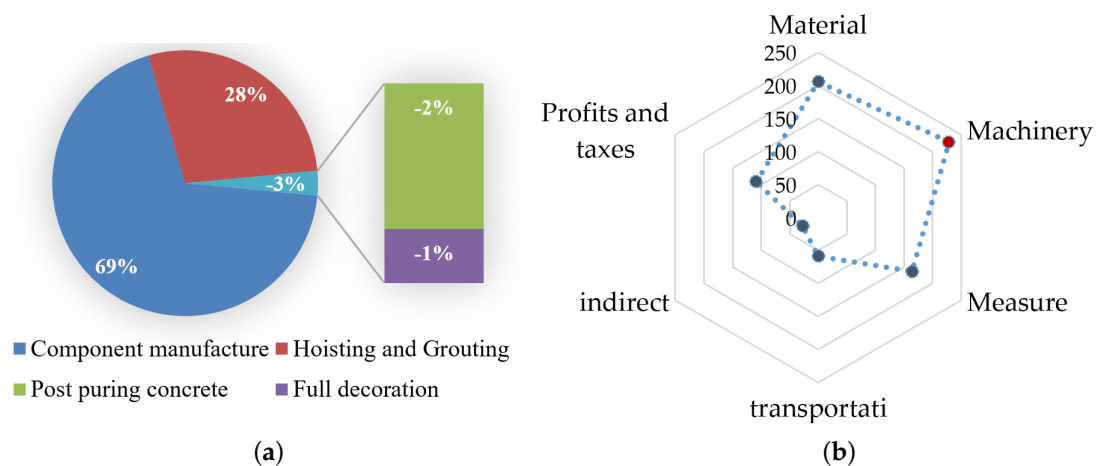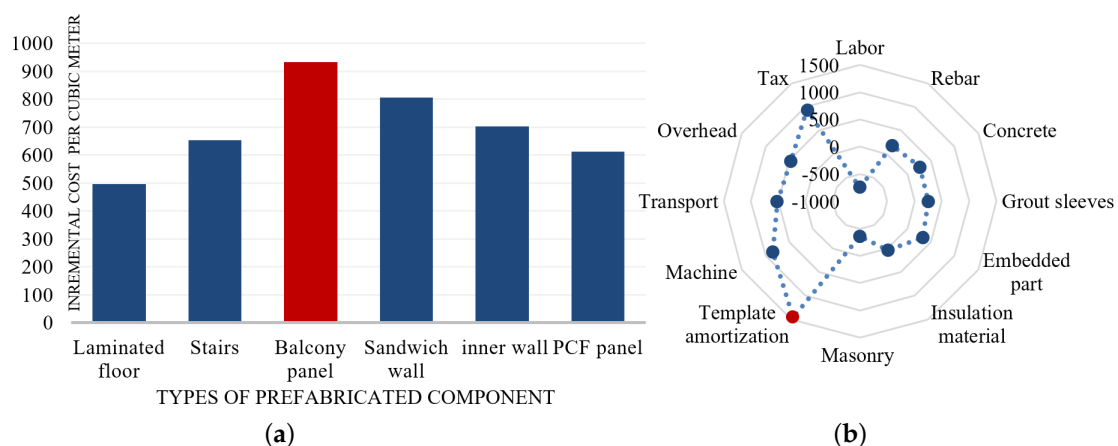
Figure 10. Proportion of the whole construction stage incremental cost and cost items. The analysis results are based on the incremental cost calculation data shown in Table 4 (yuan/m^3). (**a**) represents the incremental cost ratio of the prefabricated technologies, and (**b**) represents the incremental cost rankings of different cost items.

4.3.2. Incremental Cost Analysis of the PFC Production Stage

In this case, the incremental cost of PFC production is 4205.52 yuan/m^3. Analysis of the PFC production stage incremental cost and of cost items for each PFC type can be found in Figure 11. The manufacturing technology costs for each kind of PC component are as follows: The incremental cost of prefabricated balcony manufacture is the highest, at 932.99 yuan/m^3, which is 23% of the total incremental manufacture cost. This is followed by the incremental manufacture cost of sandwich outer and inner walls, which are respectively 806.72 yuan/m^3 and 703.25 yuan/m^3, accounting for 20% and 17% of the total incremental manufacture cost, respectively. The incremental cost of prefabricated laminated floor manufacture is the lowest, at 496.79 yuan/m^3, accounting for 11.1% of the total incremental manufacture cost.

Figure 11. Analysis of the PFC production stage incremental cost and cost items. The analysis results are based on the incremental cost calculation data in Table 5 (yuan/m^3). (**a**) represents the incremental cost rankings of factory producing incremental cost of different PFCs, and (**b**) represents the incremental cost rankings of different cost items of PFC production.

The amortization incremental cost for PFC production templates increased by a maximum of 1461.41 yuan/m^3. This is followed by the incremental costs for taxes, machinery, and transportation, which were respectively 938.39, 853.50 and 515.61 yuan/m^3. The labor cost is the reduction cost, followed by overheads, which were 744.76 yuan/m^3 and 470.65 yuan/m^3, respectively.

Recently, China's demographic dividend has decreased year on year. Since building components began to be produced in factories rather than constructed on-site, automated manufacture lines have replaced certain manual operations, such as components handling, concrete pouring, polishing, etc. This has increased the efficiency of the distribution of manufactures, improved work efficiency, reduced labor cost, and promoted the sustainable development of the construction industry. However, in order to meet split design requirements, the need for rebar and concrete volumes for prefabricated laminated floors, prefabricated sandwich exterior walls, and other components has increased, as has the need for new cost items such as embedded parts and grouting sleeves. This means that the overall cost of the PC components factory manufacture has increased. Currently, the degree of standardization of fabricated buildings in China is relatively low and the components are sold as products, which greatly increases template amortization fees and taxes. However, design difficulties will be overcome and the industrial chain is constantly improving. Incremental cost will therefore gradually decline.

4.3.3. Incremental Cost Analysis of the on-Site Assembly Construction Stage

The incremental cost of the on-site construction stage has three elements: the hoisting and grouting incremental cost, the post-cast concrete incremental cost, and the full decoration incremental cost. The incremental hoisting and grouting cost is the highest at 1702.2 yuan/m^3. The post-cast concrete and full decoration costs are negative costs, and are respectively -15.22 and -5.67 yuan/m^2. The total incremental cost of hoisting and grouting and the cost of each specific item of the PFCs are shown in Figure 12.
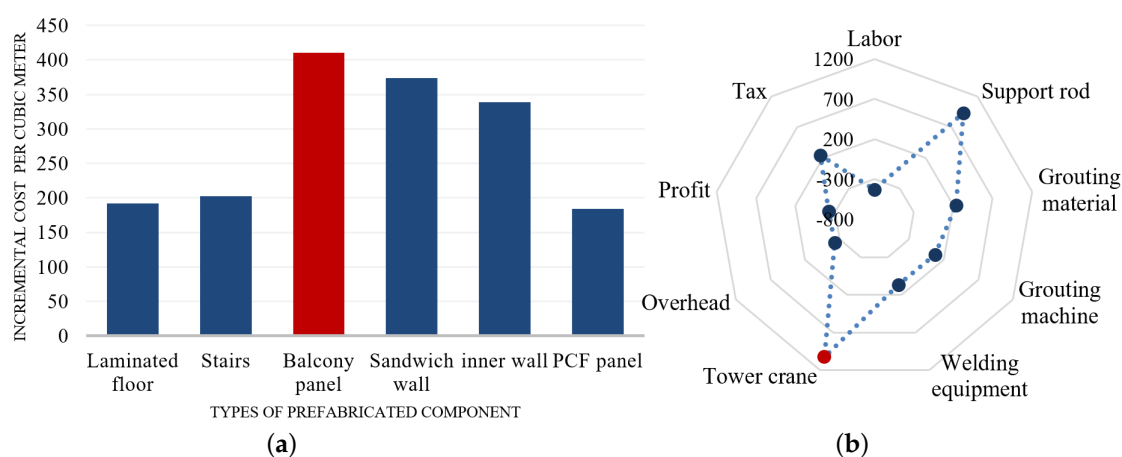

Figure 12. Incremental cost and cost items analysis of each type of hoisting and grouting PFC. The analysis results are based on incremental cost calculation data in Table 6 (yuan/m^3). (**a**) represents the incremental cost rankings of on-site assembling incremental cost of different PFCs, and (**b**) represents the incremental cost rankings of different cost items of PFC on site assembling.

The costs for the hoisting and grouting of PC components types are as follows: the increased cost of prefabricated balconies is the highest, at 410.20 yuan/m^3, accounting for 24% of the total incremental cost of hoisting and grouting. This is followed by sandwich wall and inner wall costs, which are respectively 373.91 and 338.98 yuan/m^3, accounting for 21.9% and 19.9% of the total incremental cost of hoisting and grouting respectively. PCF board incremental cost is at least 184.23 yuan/m^3, accounting for 10.8% of the total incremental cost of hoisting and grouting. This is followed by the costs of prefabricated laminated floors and prefabricated stairs, which are respectively 192.41 and 202.48 yuan/m^3, accounting for 11.4% and 12% of the total incremental cost of hoisting and grouting respectively.

Of the incremental costs, the machinery is the highest, at 1023.72 yuan/m^3, accounting for 60% of the total hoisting and grouting incremental cost. This is followed by the material incremental cost, at

925.56 yuan/m^3, accounting for 54% of the total hoisting and grouting incremental cost. The labor cost, overhead and profit are reduction costs.

Hoisting and grouting machinery incremental cost consists of tower crane and grouting equipment cost, etc. Due to the great size and fragility of PFCs, and problems resolving difficulties such as aligning reserved holes and determining slurry, the hoisting and grouting machinery incremental cost remains the highest. However, with the increase in the proficiency of hoisting work and the accumulation of experience with hoisting and grouting components, it is very conceivable that the hoisting machinery incremental cost will gradually decline.

The cost of post-pouring concrete consists of the concrete pouring cost of PFC joints and the remaining non-PFC parts of buildings. Given the fall in on-site wet work, the cost of post-pouring concrete is the reduction cost, which is −61,095.22 yuan. The PFCs are polished during factory manufacture, which can reduce the need for decorative work. Additionally, the prefabricated sandwich external walls have heat-insulating materials added at the factory, which can eliminate the need to insulate them at the construction site. The full decoration cost is thereby reduced to 22,733.27 yuan. The analysis of the post-pouring concrete and full decoration negative cost is shown in Figure 13.
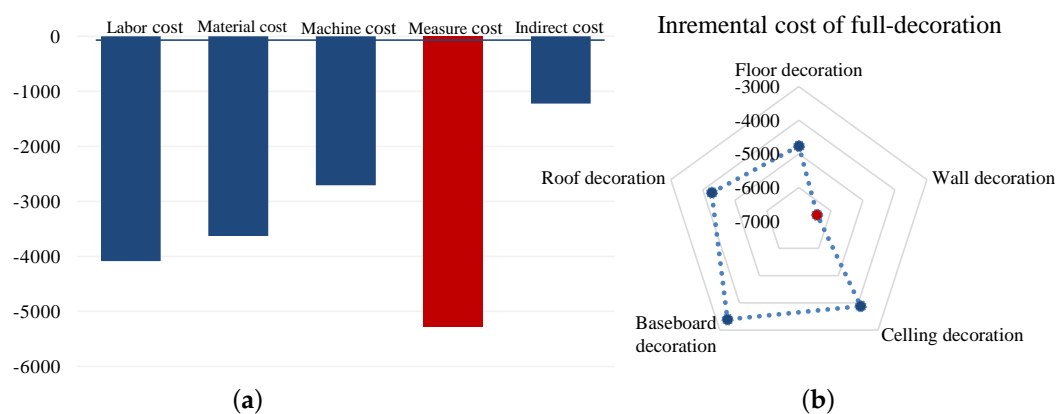

Figure 13. Analysis of incremental cost of the post pouring concrete and full decoration stage. The analysis results are based on the incremental cost calculation data in Tables 6 and 8 (yuan). (**a**) represents the incremental cost rankings of different cost items of post-pouring concrete technology, and (**b**) represents the incremental cost rankings of different full-decoration technologies.

5. Conclusions

In order to produce a more comprehensive analysis of the incremental cost of PRB, and improve the applicability of the incremental cost composition items of the whole construction stage, the most recent and authoritative PRB policy, CQ and EC are introduced. This study adopts combined qualitative and quantitative methods, those of fishbone analysis and semi-structured interview. This is done to generate a two-dimensional incremental cost index system which considers the incremental costs of all kinds of cost items and assembly technologies. A quantitative incremental cost calculation model is also developed using the BIM simulation method in order to obtain accurate calculations results. To verify the objectivity and applicability of the study results, this study also conducted a case study of an existing PRB. The following conclusions were obtained:

The composition of the whole construction stage incremental cost items includes: load-bearing and retaining walls and inner walls PFC production incremental costs, which includes labor incremental cost, material incremental cost (steer bar, concrete, grout sleeves, embedded parts, and thermal insulation parts), machinery incremental costs (fixed asset cost and manufacture line cost), measure incremental cost (formwork amortization cost), and other incremental costs (transportation fees and tax). In the on-site construction stage, the incremental cost items include: hoisting and grouting incremental cost (labor, concrete, rebar, support rod, grout material, grout machine, electric welding equipment, tower crane, formwork amortization, scaffold, overhead, profit, and tax), post pouring

concrete material cost (labor, concrete, rebar, masonry, concrete vibrator, formwork amortization, scaffold, overhead, profit, and tax), and full decoration incremental cost (labor, decoration material and decoration machinery).

The incremental cost calculation for the PRB case based on BIM simulation is 654.58 yuan/m^2, which accounts for 43.7% of the total construction cost. This calculation result is within the range of national average PRB incremental estimation results (incremental cost accounts for 20–50% of total construction cost [46]). Due to the complex structure and lower sales, the main incremental production cost can be associated with the production of prefabricated balconies. The materials and machinery cost (grout materials, support rods, grouting machines, electric welding equipment, and tower cranes) of hoisting and grouting at the on-site construction stage also increased because of inadequate technology and a lack of experience. By contrast, as a result of indirect benefits from materials (formwork, scaffold and decoration material) and labor-saving, the costs of post-concrete pouring technology and the full decoration technology at the on-site construction stage, decreased considerably. Moreover, the labor cost and overheads for the entire construction stage also decreased because of improvements in construction standardization and mechanization.

With the growing popularity of PRBs across China, and the continuing progress of assembly technology, incremental cost will naturally decrease. At the same time, there will be obvious environmental benefits. The following suggestions based on the practices of developed countries can be adopted to alleviate the current high construction incremental cost [47–49]: (1) standardized design specifications for PRBs, improved traditional split design patterns and improved standardization to reduce the formwork amortization cost; (2) the strengthening of policy support by local governments across China and the elimination of the system of duplicated taxation for PFCs, in order to reduce the sale price of PFCs; (3) the formation of a mature construction technology system in consideration of the construction habits of labor, thereby reducing tower crane and support materials costs. Therefore, further study should be initiated focusing on the relational functions for incremental cost items and its influence factors (i.e., assembly rate, incentive policies, and assembly technologies) to explore the validity of the above-mentioned suggestions, and determine the best way to reduce PRB construction cost.

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