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Research Article

Study on Complexity of Precast Concrete Components and Its Influence on Production Efficiency

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Prefabricated construction has been well recognized for its benefits, including accelerated construction cycle time and improved sustainability. However, low efficiency in the production of precast concrete components due to component and production complexity has not been sufficiently addressed in previous research. This paper explores the complexity of precast concrete components by establishing complexity indices and evaluating their influence on production efficiency. First, referring to research on product complexity in the machinery manufacturing industry, we define the complexity of precast concrete components in the construction industry. Then, based on a literature review, field studies, and expert interviews, we systematically construct the complexity indices of precast concrete components using the three-stage coding method, Grounded Theory. The overall complexity index system for precast concrete components constructed comprises 16 constituent complexity indices in three dimensions (i.e., structural complexity of the component, production complexity, and management complexity). The relationship between complexity indices and production efficiency is then explored using structural equation model analysis based on the data collected through a questionnaire survey. The results reveal that complexity indices have a significant impact on the production efficiency for precast concrete components, where the number of embedded parts, waiting time in production, operating proficiency of workers, and degree of automation of the production line are found to be the most influential complexity indices. This study provides a foundation upon which production managers improve production efficiency for precast concrete components based on an analysis of their product complexity.

1. Introduction

As an industrialized construction method, prefabricated construction entails the transfer of some onsite construction activities to an offsite manufacturing plant [1]. It has seen increasing adoption due to its increased efficiency and quality. In particular, China's prefabricated construction industry is strongly promoted by the government [2]. Precast concrete (PC) components are the basic building blocks of prefabricated concrete buildings, and the production efficiency of PC component manufacture has a direct bearing on the benefits delivered to stakeholders in the prefabricated construction supply chain. However, in the production of PC components in PC component factories, there are many complexities, such as variations in type and dimensions of the PC components, different production methods, and, correspondingly, complex production procedures [3]. These issues can lead to low production efficiency and long production cycles, which in turn hamper the development of prefabricated construction.

In recent years, a number of studies in the machinery manufacturing industry have sought to define and measure product complexity for the purpose of improving production efficiency [4]. Research on product complexity has encompassed complexity of products and production processes [5–7], as well as their impacts on production efficiency [8]. These studies considered various influencing factors on the complexity and provided a basis for improving the management of the production.

With regard to the construction industry, research on improving production efficiency in PC component factories has made great progress investigating process planning and computer-aided production process optimization [9]. Research related to product/production complexity in the construction industry mainly, though, has typically involved project complexity [10, 11], whereas there have been relatively few studies looking at the complexity of prefabricated components such as PC components. Although Ji et al. [12] proposed a hierarchical quantification method to measure common prefabricated component complexity, there is a lack of detailed analysis of the complexity for PC components. Specifically, there has been no sufficient work for systematically quantitative analysis on the complexity of PC components and its impacts during PC component design and production.

Given that PC components are complex products produced in an industrialized manner, it is beneficial to draw upon related research in the machinery manufacturing industry characterized by industrial production. In this context, in the present study we aimed to establish complexity indices for PC components and explore their impacts on production efficiency. First, the concept of PC component complexity was defined; then, the complexity indices for PC components were established using the three-stage coding method, Grounded Theory, based on a literature study and field research; finally, a model representing relationship between complexity indices and production efficiency for PC components was built using the structural equation model (SEM) method based on a questionnaire survey.

The innovations brought to bear in this study are as follows: (1) with reference to existing studies in the machinery manufacturing industry, we developed the concept of PC component complexity to aid in production management; (2) using the three-stage coding method, Grounded Theory, an innovative complexity index system for PC components was established and each index was measured; and (3) the impacts of each complexity index on component production efficiency were explored using the SEM model. This study provides a theoretical foundation for understanding PC component complexity and identifies the key complexity indices affecting production efficiency, providing a basis for effectively improving the performance of production management in PC component factories.

2. Literature Review

2.1. Production Efficiency for Precast Components. Research in the construction management field to improve production efficiency has mainly focused on production process optimization [9]. Some scholars have applied lean management in the optimization of component production lines. For instance, Wang et al. [13] identified the equipment-related, technological, and organizational issues that need to be optimized in the production process, using value flowchart technology to improve the performance of PC component production. Gallardo et al. [14] verified applications of value stream mapping, workplace organization (5S method), pull system, and total production maintenance to further improve production efficiency in PC component manufacturing. Zhang [15] established a visual simulation model for PC component production based on the Analogic platform and found the model to be capable of improving production efficiency in PC component factories.

Other researchers have adopted advanced technologies of management and operational research to solve efficiency issues in PC component production. For instance, mixed-integer linear programming (MILP) has been employed to optimize the production process [16] and to plan mold stage layouts [17], as well as for production scheduling [18]. Meanwhile, a number of studies have used intelligent algorithms for production efficiency improvement. For example, Wang and Hu [19] implemented genetic algorithm to realize production schedule optimization by integrating manufacturing, storage, and transportation from a PC component supply chain perspective. Chang and Han [20] introduced a Discrete Differential Evolution algorithm to optimize production flow in PC component production. Other notable studies in this area include a lead-time prediction model to improve production balance [21], as well as a classification system to connect market demand with production plan based on production strategy theory to improve production efficiency [22].

In recent years, building informant modeling (BIM), radio frequency identification (RFID), and other information technologies have been adopted to improve production efficiency in the manufacture of PC components. For example, Li et al. [23] established a RFID-enabled real-time BIM platform that integrates various stakeholders, offshore prefabrication processes, and information flow to improve scheduling of precast production. Du et al. [24] proposed a prefabricated component supply chain information tracking and supply mechanism based on RFID and multiagent simulation. Moreover, BIM technology and enterprise resource planning have been adopted to achieve information integration and visual management of the component production process [25, 26].

These studies have made considerable progress in terms of improving the efficiency of prefabricated component production. However, there remains a gap with respect to research identifying and analyzing complexities in the production of PC components.

2.2. Complexity of Production. A number of studies have been carried out investigating the complexity of production in the machinery manufacturing industry [4]. These studies have defined and measured complexity, uncovering the inherent complexities in production for the purpose of improving production efficiency. Hu et al. [5] proposed a complexity measurement model for products and production encompassing both the assembly system and the supply chain. Fisch and Diedrich [27] discussed strategies for assessing the complexity of production systems, presenting various examples of complexity assessment methods. Samy and ElMaraghy [6] implemented a mapping method for product assembly complexity and developed a method for evaluating and comparing assembly system complexity. Other studies have employed the methods of information entropy [7] and IOT entropy [28] to quantitatively or qualitatively investigate the complexity of products or their assembly systems.

With regard in particular to the relationship between product complexity and production performance, Senescu et al. [29] provided a method for evaluating production complexity and studied its impact on overall project complexity. Antani [30] studied the relationship between product complexity and product quality and developed an optimization model to simultaneously meet the constraints of minimum manufacturing complexity and maximum product quality. Park and Okudan Kremer [8] applied regression analysis to identify the impact of complexity on manufacturing performance under different demand and manufacturing strategies. Huang [31] took a large-scale steam turbine manufacturing company as a case study and focused on assembly complexity in studying the relationship between product complexity and man-hour quota. Yang [32] integrated several design factors, such as product complexity, product precision, and assembly costs, in exploring the influence of complexity on assembly quality. These studies have provided a strong foundation for production efficiency improvement in the machinery manufacturing industry.

3. Methodology

In the present study we set out to investigate and establish a complexity index system for PC components as the basis for analyzing the impact of PC component complexity on production efficiency. The research framework and research methods are summarized in Figure 1 below. First, we reviewed the available research on production complexity in the machinery manufacturing industry and, on this basis, proposed a conceptual definition of PC components complexity. Second, a study of the literature, field research, and expert interviews were conducted, and complexity indices for PC components were systematically established using a three-stage coding method referred to as Grounded Theory. Finally, data were collected through a questionnaire survey and analyzed using the SEM method for characterizing the relationship between complexity indices and production efficiency for PC components.

4. Complexity Index System for PC Components

The complexity index system for PC components was constructed in this section. As noted above, first, we reviewed the available literature to gain understanding of the concept of complexity and complexity indices in the context of machinery manufacturing in order to establish the theoretical basis for the present work. Then, field research was implemented, and the three-stage coding method, Grounded Theory, was used to construct the complexity index system for PC components. Finally, the complexity indices were validated and modified by conducting further interviews with the managers involved in the field study and other industry experts.

4.1. Concept of Complexity of PC Components. In current practice, there are a number of complexities inherent in the production of PC components. For example, the fact that PC components vary in structure and production cycle causes complexity in production procedures. The prerequisite for identifying and measuring the complexity index, then, is to conceptually define complexity. Complexities in the PC component production process can be identified scientifically by defining the complexity of PC components.

According to relevant research in the machinery manufacturing industry [4, 5, 25, 26], there are many aspects of product complexity and varying definitions of the concept. For instance, some scholars have understood product complexity as a state that is difficult to understand, describe, predict, or control in the product manufacturing process. Others have asserted that product complexity can be assessed simply by referring to the product's detailed design information [33]. In general, in the machinery manufacturing industry, product complexity can be divided into three categories according to its causes: product complexity, process complexity, and organizational complexity [34].

However, research on the complexity of PC components in particular, whether in the context of China or elsewhere, has been inadequate, and the concept of PC component complexity has not yet been fully defined. Ji et al. [12] defined the complexity of prefabricated components in general based on product design information as "the level of constructing difficulty based on the product's design and on the knowledge and ability an operator required to construct a product given its specific design information." In this context, prefabricated construction differs from traditional construction in that structures are built from components that are prefabricated in a factory and then transported to the construction site for assembly. As industrialized products, prefabricated components are similar to products in the machinery manufacturing industry. With reference to how product complexity has been defined within the machinery manufacturing industry, the complexity of PC components is defined in this paper as the difficulty of PC component production under the given design constraints, encompassing component design complexity, component production complexity, and management complexity.

4.2. Literature on Complexity Indices. PC component production is a complex process. To gain a better understanding, it is necessary to deconstruct the concept of PC component complexity. We thus reviewed the literature on complexity indices in order to establish the theoretical basis for our research.

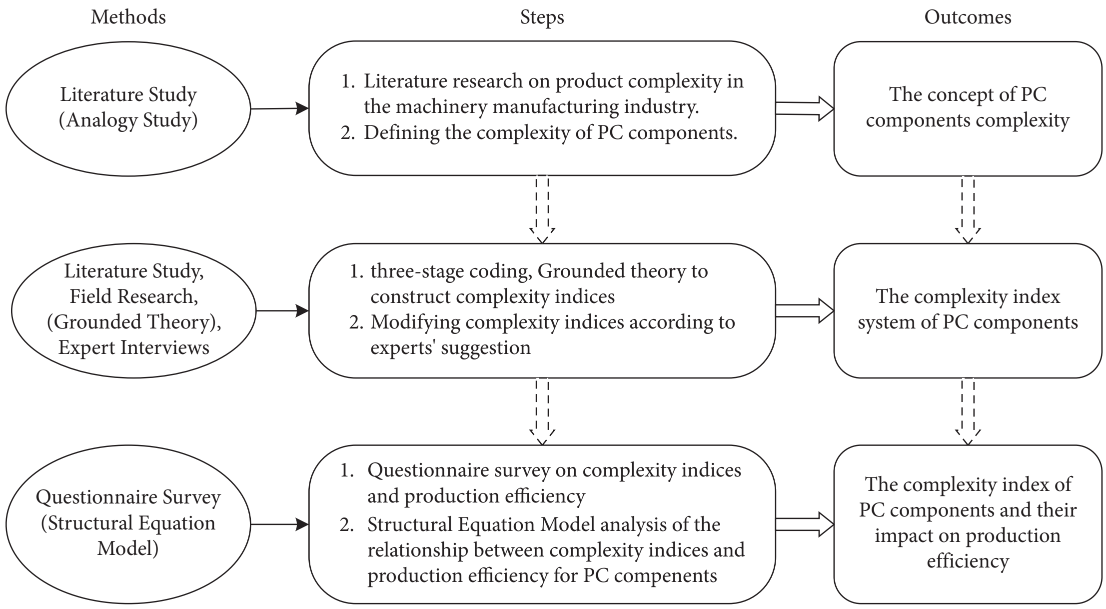

Figure 1: Workflow underlying the research methodology.

First, more than 200 publications were retrieved from the literature. Since research on the complexity of PC components in the construction industry is quite limited, the review mainly targeted product complexity in the machinery manufacturing industry. Forty-eight works with high relevance were studied, and the complexity indices of products were identified accordingly, with a particular emphasis on those related to the complexity of PC components, as shown in Table 1 below.

Most of the complexity indices listed above, though, are used for machinery products, which differ from PC components in some important respects. Therefore, field investigations in PC component factories were carried out as a further step in determining PC component complexity indices.

4.3. Construction of Complexity Index System. In addition to the literature study, field investigations were implemented. Three PC component factories were selected for the field research, which included both observation of PC component production processes and semistructured interviews with technical and managerial staff. To ensure high reliability of the interview results, only personnel with a deep understanding of PC component production processes based on six to twenty-two years of practical experience in PC component production were selected to participate in the interviews.

A qualitative approach based on Grounded Theory that included a three-stage coding method was then adopted to analyze the collected field data and construct the complexity index system for PC components. This three-stage coding included (1) open coding of first-order concepts, usually in the form of sentences summarizing the information from the original data (i.e., the initial conceptual categories for complexity were obtained by grouping and conceptualizing the sentences representing the first-order concepts); (2) axial coding, wherein the 16 initial conceptual categories for complexity obtained by open coding were divided into 3 main categories—structural complexity, production complexity, and management complexity—based on an analysis of their internal relations; and (3) selective coding, where the fundamental category, i.e., the complexity of PC components, was sorted out and any initial categories not closely related to the fundamental category were eliminated. The preliminary complexity index system was established as a result of this procedure, as described in greater detail below.

4.3.1. Open Coding. Open coding refers to the process of dividing up collected raw data, selecting relevant data, recombining the data in a new way, then analyzing, categorizing, and integrating the data into corresponding new concepts. Accordingly, in this research we first analyzed the original audio and text data collected in the interview and observation in order to encode and label it. First-order concepts were then formed by selecting and summarizing the information related to the complexity of PC components from the original data (shown in Table 2). The initial conceptual categories were obtained by conceptualizing and grouping the sentences representing the first-order concepts and with reference to complexity indices in the machinery manufacturing industry (shown in Table 1). The initial categories obtained are shown in Table 2.

4.3.2. Axial Coding. Axial coding refers to the discovery and establishment of various connections between different categories formed in open coding, including causality and similarity, to form a more general category. Accordingly, in this research, the 16 initial complexity conceptual categories (i.e., subcategories) obtained by open coding were divided into 3 main categories—structural complexity, production

Table 1: Product complexity indices from literature review.

No.	Author	Complexity index
1	Huang [31], Wang [35], Lin [36]	Product precision, surface-to-volume ratio, number of parts, assembly (production) status, assembly operation difficulty, inspection difficulty
2	Ji et al. [12], Lin [36], Fera et al. [37]	Product category and quantity, failure rate
3	Zheng [38], Fu et al. [39], Huang et al. [40]	Material consumption, difficulty in mold manufacturing
4	Zhang [15], Tian et al. [41], Meng [42], Liu and Huang [18]	Factory delivery delay/lead time, inventory, process waiting time, secondary repair rate
5	Wei [43], Yang [44], Yu [45]	Product precision, product life-span, cost, degree of automation
6	Khalili and Chua [17], Mourtzis et al. [46]	Mold manufacturing accuracy, mold turnover rate, mold arrangement time
7	Long [47], Gong [48], Zhang [49]	Number of skilled workers in production line, operating proficiency of workers
8	Wang [50], Zhou [21], Luo [51]	Mold turnover rate, degree of automation, information management level
9	Park and Okudan Kremer [8], ElMaraghy et al. [52], Wang et al. [53]	Product precision, characteristic surface area, abnormal production status
10	Zhao [33], Yan [54], Wang [55], Xie [56]	Number of parts included, number of workers, the difficulty in manufacturing and operating

complexity, and management complexity—by analyzing their internal relations. Further details concerning the conceptual categories and corresponding interpretations are shown in Table 3.

4.3.3. Selective Coding. Selective coding searches for fundamental categories in the identified categories, establishes the connection between fundamental categories and other categories, and eliminates any initial categories that are not closely related to the fundamental categories. Selecting coding was carried out in this research, resulting in the formulation of a theoretical framework as shown in Table 3.

4.3.4. Established Complexity Indices. The theoretical saturation test is the method used to test the reliability and validity of the coding methods. In this test, several different individuals code the same data, and the results are compared in order to test the consistency of the coding. In this case, five additional research team members were invited to code the original data for this purpose.

The PC component complexity indices were further validated through interviews with the management personnel who had participated in the field study, as well as with other experts from industry. The suggested revisions to the indices obtained through this process are shown in Table 4.

The final complexity index system for PC components established based on the expert revisions is shown in Table 5 below. The three categories making up the first-level index are described in greater detail below.

(1) Structural complexity refers to the complexity of the shape of the PC component. The technology for detailed design of PC components still needs to be improved. Consideration of production process requirements at the design stage is inadequate, resulting in a low standardization level of PC components. There are many types and shapes of PC components. According to the main characteristics of structural shapes of PC components in the actual production condition, surface-to-volume ratio, number of openings, number of embedded parts, reinforcement ratio, and amount of exposed rebar were identified as the indices related to structural complexity.

(2) Production complexity refers to the complexity of the production process for manufacturing the PC component. In PC component factories, there are different kinds of products, customizations, and complex production procedures, resulting in a high degree of complexity in production planning and implementation. For instance, material consumption, mold assembly time, and mold manufacturing accuracy can have a direct impact on the difficulties faced in manufacturing the molds for PC components. Moreover, when market demand for PC components is high, the production imbalance created by the differing production processes for different products can cause excess waiting time on the production line, in turn leading to schedule overruns and other production scheduling challenges. In addition, due to the intensive and complex nature of PC component production, abnormal conditions such as mechanical equipment failures and water and power outages may occur. Accordingly, material consumption, mold assembly time, mold manufacturing accuracy, waiting time in production line, and abnormal production status were identified as the indices for measuring the production complexity of PC components.

(3) Management complexity refers to the complexity of managing production in PC component factories. Currently, PC component factories in China are facing many challenges, including low operating proficiency of workers, labor shortages, low degree of mechanization and machine utilization, and inadequate information management. In particular, a lack of proficient workers in key production processes can be observed in many PC component factories. Moreover, mechanical equipment in these PC component factories is often out of use due to equipment failure caused by improper use, meaning that the machine utilization rate is relatively low. In

Table 2: Open coding process.

No.	Initial category	First-order concept (interview and observation)
1	Component size (surface-to-volume ratio)	01 Currently, the standardization level of PC components is low. Some components have large surface-to-volume ratios and the component structural design is very complicated. The specific production processes and manufacturing techniques may not be fully considered in detailed design stage. Such components need a long production duration. 09 Different kinds and sizes of components increase production cost and time of molds. Some large and complex components require 3-4 days to produce.
2	Number of openings, number of sections	08 Some components are designed with many openings, unique shapes, and many sections, which increase the difficulty in mold production and the time of mold assembly.
3	Number of embedded parts	01 Normally, the numbers and location of embedded parts directly affect design and assembly complexity of molds. 10 Some components need redesigning and reproduction due to the inappropriate placement of embedded parts in PC components, which does not meet the construction requirements.
4	Reinforcement ratio	03 Steel rebar is the main material of a PC component and the amount of rebar contained directly reflects the structural complexity. For components with a larger amount of rebar, the time required for binding and processing is comparatively long.
5	Waiting time in production line	01 There is a waiting time for inspection and warehousing after mold removal. The waiting time for rebar binding is another circumstance. These all lead to inefficiency. 06 Assembly lines mainly produce components of laminated panels and in-line walls in factories. The degree of automation is relatively high. However, different production processes for these two main components can cause waiting time when demand is high.
6	Material consumption	06 Generally, components with more materials require longer production time and face greater production difficulty which results from production complexity.
7	Abnormal production status	05 Force Majeure factors, such as equipment failures and water and power outages may occur in the production process. That will increase the production complexity and inefficiency. 07 In Beijing, Force Majeure factors are, for example, haze, low temperature, lower production efficiency.
8	Improper delivery time	10 Components produced ahead of schedule may not be able to be shipped in time, resulting in the accumulation of finished products in factories. That may affect the production cycle.
9	Stocking	02 The backlog of finished components increases the stock, disrupts production plans, and causes inefficiency.
10	Mold turnover rate	08 Low reuse rates of molds are common today. The customized molds increase the management complexity in component production. 09 The turnover time of fixed vibration platforms, such as for exterior walls, stairs, and balcony panels, is relatively long, resulting in decreases in reuse rates of molds.
11	Repair rate (quality defect)	03 Some factories are in short of component supply causing rush work; therefore the proportion of products returned to the factory or scrapped (due to quality issue) is quite large. Complex components are prone to crack, contain bubbles, and have unqualified dimensions. A repair area is required for those components, increasing the complexity in the production arrangements. 04 If the finished products are identified as unqualified ones in the test before delivering, they will need reproduction. This may disrupt the original production plan.
12	Mold manufacturing accuracy	04 Currently, component molds are outsourced to mold factories to produce. The manufacturing factories conduct accuracy inspections before mold use. A low accuracy level will cause severe damage in production. Those molds with large errors cannot be used and need reproduction. 05 Some manufacturing factories may produce all the molds by themselves, which can achieve high mold accuracy and avoid the cost and waste caused by insufficient mold accuracy.
13	Mold assembly time	10 Mold removal is typically carried out manually, and this takes a long time, especially for complex components. 01 The mold assembly time for complex components is different, which may affect production efficiency.
14	Degree of automation of production line	01 Automation equipment is out of use in some PC component factories, resulting in an increased reliance on manual operations. A large number of manual operations will extend the production duration and lower production efficiency. 07 Automation levels of assembly lines in PC component factories today are relatively high. However, stairs and sandwich wall panels are normally produced on fixed vibration platforms. Some processes such as mold removal and mold assembly are still manually operated. If full automation can be achieved, production efficiency can be significantly improved and the complexity in production management will be reduced.
15	Operating proficiency of workers	09 Workers in PC component factories are hired from labor service companies. Their operational proficiency of workers will directly affect production efficiency. 02 Managerial and technical personnel in PC component factories are usually qualified, whereas others are sometimes new migrant workers, which increases the difficulty in training and management.

Table 2: Continued.

No.	Initial category	First-order concept (interview and observation)
16	Information management level	11 Intelligent information management system is adopted in many PC component factories. However, some data and information fail to upload in time, and this increases the management complexity in component production. 03 Most of the data in factories are still recorded using a paper-and-pencil method, meaning that data can be easily misplaced. Moreover, some information is not recorded in time, resulting in delayed information transmission and increased management complexity.

Table 3: Results of axial coding and selective coding.

Fundamental category	Main category	Subcategory (initial category)	Interpretation
Complexity of PC components	Structural complexity	Surface-to-volume ratio	The structural design is very complicated. The standardized production processes and manufacturing techniques may not be fully considered with detailed design
		Number of openings, number of sections	Too many openings and cross-sections
		Reinforcement ratio	Component reinforcement ratio reflects structural complexity
		Number of embedded parts	Number of embedded parts in components
		Material consumption	Large components require more embedded parts, rebar, and concrete
	Production complexity	Mold assembly time	Time for manual assembly and removal of molds
		Mold manufacturing accuracy	Mold precision check
		Waiting time in production line	Waiting time for each procedure in the production line
		Abnormal production status	Force Majeure factors such as equipment failures cause abnormal conditions in component production
	Management complexity	Operating proficiency of workers	Experience and operational proficiency of workers
		Mold turnover rate	Long turnover time and low mold reuse rates of molds
		Stocking	Accumulation of finished components
		Improper delivery time	Components leave factories ahead of or behind the schedule, disrupting the production cycle
		Repair rate	Repairs or reproduction of finished components due to quality defects
		Degree of automation of production line	Equipment utilization rate in production line
		Information management level	Timeliness and accuracy of component production data transmission

other words, PC component production in China is still heavily reliant on human effort. In addition, communication among workers and between management and workers during production is usually oral, meaning that it lacks accuracy and is not recorded. Moreover, production procedures in some PC component factories are not well integrated, and this can lead to miscommunication of information concerning the production process. As a result, quality control issues often go undetected, resulting in unnecessary repair or reproduction. Furthermore, it is difficult to control mold turnover and to avoid delivery delays, given these existing challenges. Accordingly, operating proficiency of workers, mold turnover rate, delivery delay, repair rate, degree of automation of production line, and information management levels were identified as the indices for management complexity.

4.4. Measurement of Complexity Indices. The complexity indices established in this research can be categorized as either qualitative indices or quantitative indices, where quantitative indices are directly measurable based on their inherent quantitative characteristics in terms of a specific physical unit (e.g., piece, minute, etc.), whereas qualitative indices are measured based on subjective judgments and there is no specific unit. Most of the indices identified in this research are quantitative indices and can be directly measured. For example, the number of openings is measured based on its own quantitative characteristics. Other quantitative indices—such as mold manufacturing accuracy, abnormal production status, operating proficiency of workers, and degree of automation of production line—while more complex, can still be quantitatively measured. For instance, (1) features of molds such as size and flatness are usually inspected during assembly, and feedback is recorded in real

TABLE 4: Additional revisions to some indices.

Revision	Reason
Delete "number of sections"	The increase in the number of openings will increase the number of sections. The indices are repeated, and the number of openings is easier to measure.
Delete "stocking"	Stocking is for the entire factory, and an individual component cannot be measured in this dimension.
Add "amount of exposed rebar"	The amount of exposed rebar can reflect the structural complexity, which is related to the stability and bearing capacity of PC components and will also affect design and assembly of molds.
"Improper delivery time" is revised to "delivery delay"	In current practice, there are almost no cases where components are shipped in advance. In other words, the index is meaningless.

TABLE 5: Final complexity index system for PC components.

First-level index (from main category)	Second-level index (from subcategory)
Structural complexity D1	Surface-to-volume ratio F11, number of openings F12, reinforcement ratio F13, number of embedded parts F14, amount of exposed rebar F15
Production complexity D2	Material consumption F21, mold assembly time F22, mold manufacturing accuracy F23, waiting time in production line F24, abnormal production status F25
Management complexity D3	Operating proficiency of workers F31, mold turnover rate F32, delivery delay F33, repair rate F34, degree of automation of production line F35, information management level F36

time. The error value directly reflects the accuracy of the molds. Therefore, the accuracy of mold manufacturing can be quantified as the mean value of inspection errors. (2) PC component production involves many complex processes. Abnormal production status caused by Force Majeure factors such as equipment failures is unavoidable. Thus, the abnormal status in production can be quantified as the frequency of occurrence of abnormal and adverse situations in the production of PC components. (3) The operational proficiency of front-line workers, meanwhile, is typically a function of experience (i.e., length of employment). In other words, working hours are positively correlated with operational proficiency. Therefore, operating proficiency of workers can be quantified as the average working years in the PC industry of front-line workers. (4) In PC component production, different types of PC components require different production methods, as noted above. Components such as laminated panels and precast interior wall panels are often produced in assembly lines, whereas other types of components, such as exterior wall panels and stairs, are usually produced on a fixed vibration platform. Thus, the degree of automation of production lines varies. Meanwhile, automated mechanical equipment in some factories may be idle due to malfunctions caused by improper use, with the result that mechanical operations are replaced by manual operations. The degree of automation of production line can be quantified as the utilization rate of the mechanical equipment.

The information management level of PC component production, meanwhile, is a qualitative index, meaning that it cannot be directly quantified based on objective data. Thus, the Likert Scale method was adopted in our research for the purpose of qualitative assessment of this index. Timeliness and accuracy of data transmission during PC component production were assessed on a five-point scale: 2 (low), 4 (comparatively low), 6 (normal), 8 (comparatively high), and 10 (high). The complexity index measurement of PC components is shown in Table 6.

The conceptual definition of PC component complexity based on the literature research was provided in this section. According to this definition, the primary complexity index system for PC components was established using Grounded Theory.

5. Model of Relationship between Complexity Indices and Production Efficiency for PC Components

The fact that different kinds of PC components differ in structural complexity, and, correspondingly, complexity of production and factory management, leads to low production efficiency. Based on our work developing complexity indices for PC components as described above, a questionnaire survey was then administered, and the data was analyzed using the SEM method to confirm the complexity index system and identify the key complexity indices affecting production efficiency.

5.1. Theoretical Basis and Research Hypotheses

5.1.1. Applicability and Assumption of Structural Equation Model. SEM can be used to analyze an entire set of relationships between variables based on covariance matrices constructed. SEM is a multivariate statistical modeling method integrating factor analysis and path analysis in which latent variables can be measured by observed variables, measurement errors are allowed, and the entire model's fitness can be estimated [57, 58]. Based on the above characteristics, in this study, SEM was used to test a hypothesized model for understanding complexity indices and their impacts on the efficiency of PC component production.

Table 6: Complexity index measurement of PC components.

First-level index	Second-level index	Index measurement method	Unit
Structural complexity D1	Surface-to-volume ratio F11	Ratio of surface area to volume of a component	%
	Number of openings F12	Number of openings in a component	Piece
	Reinforcement ratio F13	Ratio of longitudinal rebar' area to effective area in a component's cross section	%
	Number of embedded parts F14	Total number of embedded parts in a component	Piece
	Amount of exposed rebar F15	Weight of rebar exposed of a component	kg
Production complexity D2	Material consumption F21	Consumption cost of rebar, concrete, and embedded parts for a component	1000 RMB/m^3
	Mold assembly time F22	Average time required to assemble molds of a component	min/m^3
	Mold manufacturing accuracy F23	Average error of mold precision tests for a component	mm
	Waiting time in production line F24	Average waiting time in all production processes for a component	min
	Abnormal production status F25	Average frequency of abnormal status during the production for a component (such as mechanical equipment failures and water and power outages)	Time
Management complexity D3	Operating proficiency of workers F31	Average working years of first-line workers of a component	Year
	Mold turnover rate F32	Average time duration for the mold to be used once	Day/time
	Delivery delay F33	Average delivery delay time of a component	Day
	Repair rate F34	Number of components needing repair per 100 pieces of the component due to quality issues	%
	Degree of automation of production line F35	Ratio of mechanized operation procedures to total procedures of a component	%
	Information management level F36	Timeliness and accuracy of information transmission for a component, which is divided into five levels: low, comparatively low, normal, comparatively high, and high	2, 4, 6, 8, and 10

In the model, the latent variables, i.e., the first-level complexity indices of structural complexity, production complexity, and management complexity, were observed in light of second-level complexity indices. On this basis, the relationships between observed variables, latent variables, and production efficiency were further characterized.

In general, the following assumptions are required to ensure the accuracy of SEM analysis results [58, 59]: (1) SEM is a confirmatory analysis method, meaning that a theoretical foundation or support from other methods is usually required in order to establish the hypothetical model. This study established the initial complexity indices and their relationships with production efficiency based on a literature review and field study. (2) SEM verifies the degree of fitness between a sample covariance matrix and the covariance matrix of the hypothetical model. The variables need to have a normal distribution. In this research, a sample size of more than 150 was used to ensure a normal distribution of data. (3) The absolute value of the correlation coefficient between latent variables should not be close to 1. In our research, this criterion was met based on the following statistical analysis while implementing SEM. (4) SEM examines model fitness in order to verify the degree of matching between the sample data and the hypothetical model. In our study, we used χ^2/df, Incremental Fit Index (IFI), Tucker-Lewis Index (TLI), Comparative Fit Index (CFI), and Root Mean Square Error Approximation (RMSEA) to test the overall fitness of the model. These were verified in the subsequent analysis.

5.1.2. Theoretical Analysis and Research Hypothesis. Theoretical analysis of the relationship between production efficiency and PC component complexity, including structural complexity, production complexity, and management efficiency, was carried out as the basis for formulating the hypothesis.

(1) Analysis of the Impact of Structural Complexity on Production Efficiency

Prefabricated buildings have changed manner of construction compared to traditional cast-in-situ construction. It is thus necessary to give careful consideration to the PC component production process requirements when conducting detailed design of PC components. If the design of components is complex, there will be a low level of standardization in their production. Moreover, increasing variety in component types will increase the mold design burden, decrease mold standardization, and ultimately lead to a reduced mold turnover rate. In other words, production difficulties have increased as PC components have increased in intricacy and variability over time. In this regard, scholars have noted that the structural design of PC components will affect its production efficiency or, more specifically, that a more complex structural design of the component will result in a lower production efficiency [17, 60].

(2) Analysis of the Impact of Production Complexity on Production Efficiency

As an industrialized process, PC component production is a flow operation with many procedures for different products. According to field surveys, different kinds of components require different production procedures, and it is difficult to arrange efficient production with so many kinds and shapes of components. Meanwhile, increased market demand intensifies the complexity of the production planning, in turn leading to an imbalanced production cycle, longer production duration, and lower efficiency. Cheng et al. [61] asserted in this regard that imbalance in terms of the varying production times for various products causes excess waiting time in production, thereby reducing production efficiency considerably. In addition, large and uniquely shaped components will further increase the complexity of component production, further hampering production efficiency due to the increased manual work involved [49].

(3) Analysis of the Impact of Management Complexity on Production Efficiency

The production of PC components entails several challenges related to production management, including complex production procedures, a large amount of process information, and high requirements for staff collaboration. Also, different PC component factories have different levels of automation, and it is difficult to manage production in a setting where there is a significant reliance on both machines and manual effort. Therefore, to improve production efficiency, problems in production management need to be identified [42], and personnel management, organizational structure, and information management need to be improved. Our field investigation showed that management complexity is common in busy factories. Workers in different production lines walked freely and did not follow the operation direction, causing disorder in terms of production management. This, in turn, is reflected in the product quality, where avoidable rework is often required. Moreover, information exchange is typically through paper-and-pencil and oral communication methods, resulting in low data accuracy and delays in transmission of production data.

(4) Theoretical Hypotheses concerning the Relationship between Complexity Indices and Production Efficiency

As per literature review and field interviews discussed above, it is apparent that structural complexity, production complexity, and management complexity all have adverse effects on the efficiency of PC component production. However, most previous analyses have been conducted on only a theoretical level, whereas empirical study is necessary in order to verify the relationship between complexity and production efficiency. For this purpose, we formulated a series of hypotheses as follows: (1) H1: the structural complexity of PC components has a negative impact on production efficiency, where a higher degree of structural complexity results in lower production efficiency; (2) H2: complexity in the PC component production process has a negative impact on production efficiency, where a higher degree of production complexity results in lower production efficiency; and (3) H3: the complexity of production management in the production of PC components has a negative impact on production efficiency, where a higher degree of complexity of production management results in a lower production efficiency.

The theoretical model of complexity indices for PC components and their impacts on production efficiency that was built based on these hypotheses is shown in Figure 2. The first-level complexity indices—i.e., structural complexity, production complexity, and management complexity—were used as the latent variables in the theoretical model. Those can be observed in light of second-level complexity indices. This theoretical model, in turn, served as the basis for further discussion of the relationships between observed variables, latent variables, and production efficiency.

5.2. Questionnaire and Data

5.2.1. Questionnaire Design and Data Collection. Based on the established complexity indices for PC components, we employed SEM to verify the relationship between complexity indices and production efficiency. The first-level indices of prefabricated component complexity and production efficiency were used as latent variables, while the second-level indices were used as the observed variables of the latent variables. A Likert Scale was used in the questionnaire in which a score of "1" means there is no influence, "2" a slight influence, "3" a medium influence, "4" a great influence, and "5" a significant influence.

Respondents consisted of (1) technicians and management personnel from PC component factories and (2) scientific researchers engaged in prefabricated construction research. All respondents had a deep understanding of PC component production processes and technologies, and this helped to ensure the reliability and validity of the questionnaire data. The respondents represented different organizations, different educational backgrounds, and different age cohorts. The questionnaires were distributed through WeChat or emails or conducted face-to-face. A total of 210 questionnaires were distributed or administered, and 182 valid responses were obtained, accounting for 86.67% of the total number.

5.2.2. Reliability and Validity Test. The questionnaire data were processed using SPSS 25.0 software as described in greater detail below, and the reliability of the questionnaire was further confirmed using Cronbach's alpha test. Cronbach's alpha coefficient was found to be 0.885, and

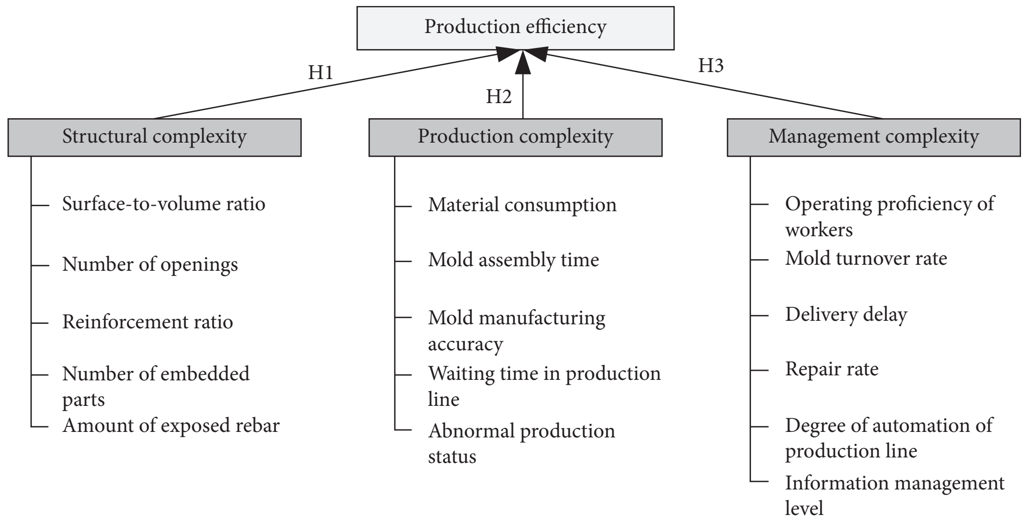

Figure 2: Theoretical model of the influence of PC component complexity on production efficiency.

Cronbach's α value >0.700, meaning that the collected data was found to be both reliable and valid. After testing the reliability of the observed variables, the reliability of each latent variable was tested. As shown in Table 7, Cronbach's α values of the three latent variables are all greater than 0.700, indicating the reliability of the latent variables. In summary, all observed variables and latent variables were found to have a sufficient level of reliability to proceed with the SEM analysis.

Prior to further analysis, it is advisable for the validity of the data to be tested using KMO (Kaiser-Meyer-Olkin) measurement and Bartlett's test for sphericity. Both of these tests were performed using SPSS 25.0 software (see Table 8). As shown in the table tested KMO value was found to be 0.816 (>0.7), while the tested Bartlett sphere value was 0.000 (<0.001, significant), which means that the data reaches the validity standard and is suitable for factor analysis.

5.3. *Structural Equation Model for Complexity Indices and Production Efficiency*

5.3.1. First-Order CFA Model. The first step in SEM is confirmatory factor analysis (CFA), where first-order CFA is used to test the relationship between observed variables and latent variables. In this research, CFA was carried out using AMOS24.0 software, with the CFA standardized model obtained shown in Figure 3, where the double arrows indicate the relationships among the latent variables. The fitness of the model was then tested, and the test values are shown in Table 9.

It can be seen from the table above that the fitness index values (χ^2/df, IFI, TLI, CFI, and RMSEA) of the first-order CFA were all within the acceptable range, indicating the rationality of the model. Therefore, the complexity index system model with two-level indices was found to be reasonable.

5.3.2. Second-Order CFA Model. According to the results of the first-order CFA, positive relationships were identified among the variables of structural complexity, production complexity, and management complexity. Therefore, second-order CFA was implemented to analyze the relationship between structural complexity, production complexity, and management complexity and production efficiency. The second-order CFA model was built using AMOS24.0 software as shown in Figure 4. The model fitness was tested, and the test values of the second-order model are shown in Table 10.

Table 7: Reliability test of latent variables.

Latent variables	Number of observed variables	Cronbach's α
Structural complexity	5	0.909
Production complexity	5	0.906
Management complexity	6	0.923

As shown in Table 10, χ^2/df is 1.181, and the fitness indices (i.e., TLI, CFI, IFI) were all found to be within the standard range. Thus, the goodness-of-fit was excellent, and the second-order CFA model was deemed acceptable. In CFA, it should be noted that the values of the path coefficients *r* and *p* in the results can be used to evaluate whether the proposed theoretical relationship is valid. More specifically, the *p* value is used to assess whether the consistency test is passed, and the r-value is used to reflect interaction effects among the variables. In this context, the significance test results of each hypothesis proposed in this research are shown in Table 11.

The *p* values of the hypotheses in Table 11 were all found to be less than 0.001, indicating that all the hypotheses proposed in this research are valid. As shown in Figure 4, the influence path coefficients of structural complexity, production complexity, and management complexity with production efficiency were found to be −0.54, −0.53, and −0.61, respectively—all less than -0.5. Thus, the impact they have on production efficiency is significantly negative.

5.3.3. Influence Weights of Complexity Indices on Production Efficiency. It can be seen from the path coefficients in Figure 4 that the influence of each complexity index was found to be very significant. The path coefficients were used

Table 8: KMO and Bartlett tests.

Kaiser-Meyer-Olkin measure of sampling adequacy	0.816
Bartlett's test for sphericity (significance level)	0.000

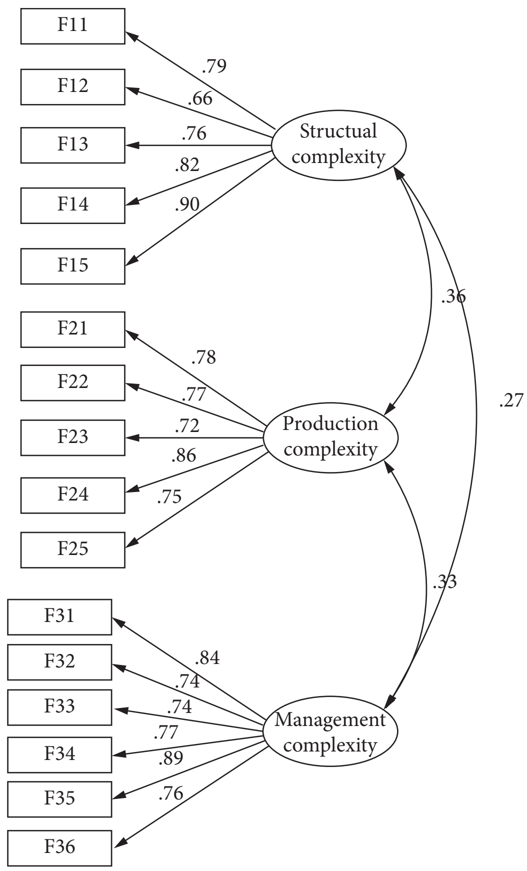

Figure 3: First-order CFA standardized model for the complexity index system.

Table 9: Goodness-of-fit test for the first-order CFA model.

	χ^2/df	IFI	TLI	CFI	RMSEA
Standard level	1–3	>0.9	>0.9	>0.9	<0.08
Tested level	1.230	0.958	0.948	0.956	0.070
Goodness-of-fit	Fit	Fit	Fit	Fit	Fit

to further obtain the influence weight of each second-level complexity index on production efficiency. The weighted average algorithm was used under the following assumptions:

(1) Assume that the path coefficient between the three first-order latent variables and the second-order latent variable is Pi ($i = 1, 2, 3$).

(2) Assume that the path coefficients between the three first-order latent variables and their corresponding observed variables (F11 ~ F36) is Pi, j ($i = 1, 2, 3; j = 1, 2, \ldots, n$), where n is the number of observed variables contained in each first-order latent variable.

(3) Assume that the contribution value of the three first-order latent variables to the second-order latent variables is Weight 1, Qi.

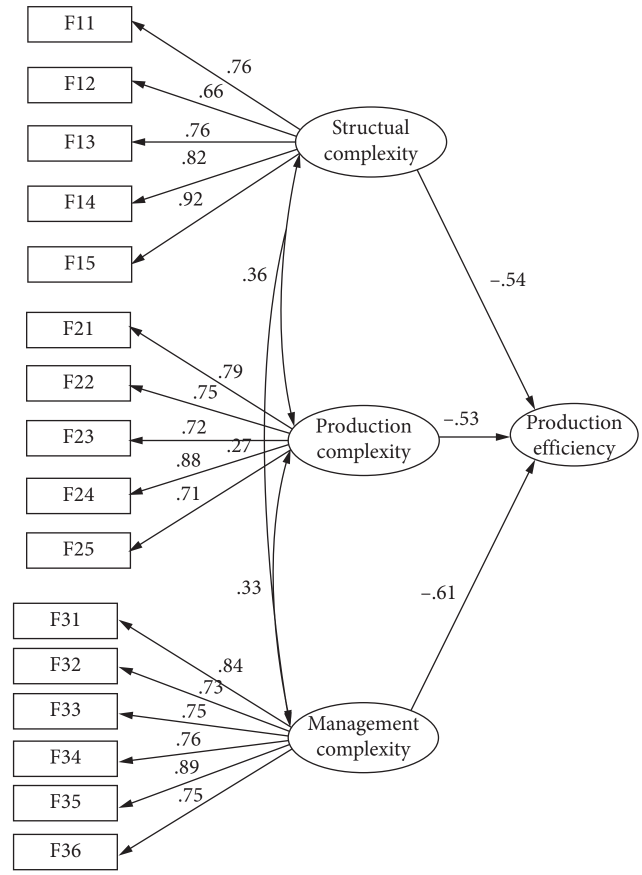

Figure 4: Second-order CFA standardized model for complexity indices with production efficiency.

Table 10: Goodness-of-fit test for the second-order CFA model.

	χ^2/df	IFI	TLI	CFI	RMSEA
Standard level	1–3	>0.9	>0.9	>0.9	<0.08
Tested level	1.181	0.970	0.963	0.969	0.062
Goodness-of-fit	Fit	Fit	Fit	Fit	Fit

(4) Assume that the contribution value of each observed variable (F11 ~ F36) to its corresponding first-order latent variable is Weight 2, Qi,j.

(5) Assume that the contribution value of each observed variable (F11 ~ F36) to the second-order latent variable is Total Weight, Qj.

Accordingly, Weight 1, Weight 2, and Total Weight could be calculated as follows:

$$\begin{aligned}
&\text{Weight 1}: Q_i = \frac{P_i}{\sum_{i=1}^{3} P_i}, \ (\mathrm{i} = 1, 2, 3),\\
&\text{Weight 2}: Q_{i,j} = \frac{P_{i,j}}{\sum_{j=1}^{n} P_{i,j}}, \ (\text{n is the number of observed variables contained in each first-order latent variable.}),\\
&\text{Total Weight}: Q_j = Q_i \times Q_{i,j}.
\end{aligned} \tag{1}$$

The relationship weights between the complexity indices and production efficiency were calculated as shown above

Table 11: Path coefficient and hypothesis test of the relationship between complexity index and production efficiency.

Hypothesis	Standardization coefficient	p value	Test result	Note
Production efficiency ← structural complexity	−0.544	<0.001	Significance	The negative correlation
Production efficiency ← production complexity	−0.532	<0.001	Significance	can influence
Production efficiency ← management complexity	−0.609	<0.001	Significance	the hypothesis reliability

(see Table 12 for the calculated weights). The weight ranking was established according to weight values in order to determine the influencing sequence of the complexity indices affecting production efficiency.

5.4. Results and Discussion

5.4.1. Results. SEM combines factor analysis and path analysis. The results of the SEM analysis in this study proved the rationality of the two-level complexity indices and their significantly negative correlation with the production efficiency (see Figure 5). It can be seen from Tables 9 and 10 that the fitness index values (χ^2/df, IFI, TLI, CFI, and RMSEA) of the first-order CFA and the second-order CFA were all found to be within the acceptable range, indicating the rationality of the SEM in Figure 4. As can be seen from Table 11, the p values of all the hypotheses were found to be less than 0.001, confirming their validity. The influence path coefficients of structural complexity, production complexity, and management complexity of PC components on production efficiency, meanwhile, were found to be −0.54, −0.53, and −0.61, respectively, and the p values were all far less than 0.01. Moreover, the weight of the complexity index was calculated in order to obtain the ranking of the impact weight of each of the second-level complexity indices on production efficiency. The top 5 weights in terms of production efficiency impact were F15 (amount of exposed rebar), F24 (waiting time in production line), F35 (degree of automation of production line), F14 (number of embedded parts), and F31 (operating proficiency of workers), as shown in Figure 5.

(1) Inspection Results for Structural Complexity of PC Components

The influence path coefficient of structural complexity of PC components on production efficiency was found to be −0.54, indicating that structural complexity has a significantly negative impact on production efficiency. Among the second-level complexity indices of structural complexity of PC components, amount of exposed rebar (F15) and number of embedded parts (F14) were found to have the greatest impacts, with path coefficients of 0.92 and 0.82, respectively. The coefficients of surface-to-volume ratio (F11), reinforcement ratio (F13), and number of openings (F12), meanwhile, were found to be 0.76, 0.76, and 0.66, respectively.

(2) Inspection Results for Production Complexity of PC Components

The influence path coefficient of production complexity of PC components on production efficiency was found to be −0.53, indicating a significantly negative impact on production efficiency. Among the second-level complexity indices of production complexity of PC components, waiting time in production line (F24) was found to have the greatest impact, with a path coefficient of 0.88. The coefficients of the other second-level complexity indices of production complexity, i.e., material consumption (F21), mold assembly time (F22), mold manufacturing accuracy (F23), and abnormal production status (F25), were found to be 0.79, 0.75, 0.72, and 0.71, respectively.

(3) Inspection Results for Management Complexity of PC Components

The influence path coefficient of management complexity of PC components on production efficiency was found to be −0.61, indicating that management complexity has a significantly negative impact on production efficiency. Among the second-level complexity index of management complexity of PC components, degree of automation of production line (F35) and operating proficiency of workers (F31) were found to have the greatest impacts, with path coefficients of 0.89 and 0.84, respectively. The coefficients of the other second-level complexity indices of management complexity, i.e., repair rate (F34), information management level (F36), delivery delay (F33), and mold turnover rate (F32), were found to be 0.76, 0.75, 0.75, and 0.73, respectively.

5.4.2. Discussion. The findings from the SEM analysis contained meaningful information about the complexities of a PC component during its production that can be leveraged to contribute to production management and improved efficiency for PC component production.

(1) Influence of Structural Complexity on Production Efficiency

According to the test results, it was determined that the structural complexity of PC components has a significant negative impact on production efficiency. In general, structural complexity can be reduced by elevating the degree of standardization, which in turn can be achieved by improving in-depth design techniques for PC components.

Among the second-level structural complexity indices, number of embedded parts and amount of exposed rebar were found to have the greatest influence. Excessive exposed rebar is mainly used for important loading-bearing components. With the technology advancements being seen today with

Table 12: Ranking for the influence weights of the complexity indices on production efficiency.

First-level complexity indices (latent variable)	Second-order path coefficient *Pi*	Weight of first-level indices *Qi*	Second-level complexity indices (observed variables)	First-order path coefficient *Pi,j*	Weight of second-level indices *Qi,j*	Ranking of *Qi,j*	Total weights, *Qj*	Ranking of *Qj*
Structural complexity D1	−0.54	0.321	Surface-to-volume ratio F11	0.76	0.194	4	0.062	7
			Number of openings F12	0.66	0.168	5	0.054	16
			Reinforcement ratio F13	0.76	0.194	3	0.062	8
			The number of embedded parts F14	0.82	0.209	2	0.067	4
			Amount of exposed rebar F15	0.92	0.235	1	0.076	1
Production complexity D2	−0.53	0.316	Material consumption F21	0.79	0.205	2	0.065	6
			Mold assembly time F22	0.75	0.195	3	0.061	9
			Mold manufacturing accuracy F23	0.72	0.187	4	0.059	10
			Waiting time in production line F24	0.88	0.229	1	0.072	2
			Abnormal production status F25	0.71	0.184	5	0.058	11
Management complexity D3	−0.61	0.363	Operating proficiency of workers F31	0.84	0.178	2	0.065	5
			Mold turnover rate F32	0.73	0.155	6	0.056	15
			Delivery delay F33	0.75	0.159	5	0.058	12
			Repair rate F34	0.76	0.161	3	0.058	13
			Degree of automation of production line F35	0.89	0.188	1	0.069	3
			Information management level F36	0.75	0.159	4	0.058	14

respect to the connections for PC components in construction [62–64], prefabricated construction has been developing rapidly. However, due to the low level of standardization of component production, having a wide variety of components increases the difficulty in mold design and production, rebar configuration, and binding. Accordingly, the reduced mold turnover rate results in low production efficiency. Therefore, some of the important loading-bearing components with excessive exposed rebar may not be suitable for manufacturing production and should instead be cast in place on the construction site. In the detailed design of PC components, BIM and other technologies could be used to assist in standardized component design [21, 40, 65] in order to reduce the number of different component types and thereby decrease the structural complexity [66].

(2) Influence of Production Complexity on Production Efficiency

From the test results, it was determined that production complexity of PC components has a negative impact on production efficiency. The field investigation showed that the reasonable optimization of production scheduling of PC components can be helpful as a means of reducing the complexity of PC component production.

With regard to the second-level complexity indices of production complexity, waiting time in production line was found to have the greatest impact on production efficiency. Imbalanced processing times in production lines depending on the type of component cause complexity in the production plan, and the resulting long waiting times in the production line have a significant influence on the production efficiency. This brings challenges in terms of production planning. The wide variety of components combined with high demand in China's PC industry in particular only exacerbates the issue of imbalanced processing time and reduces production efficiency

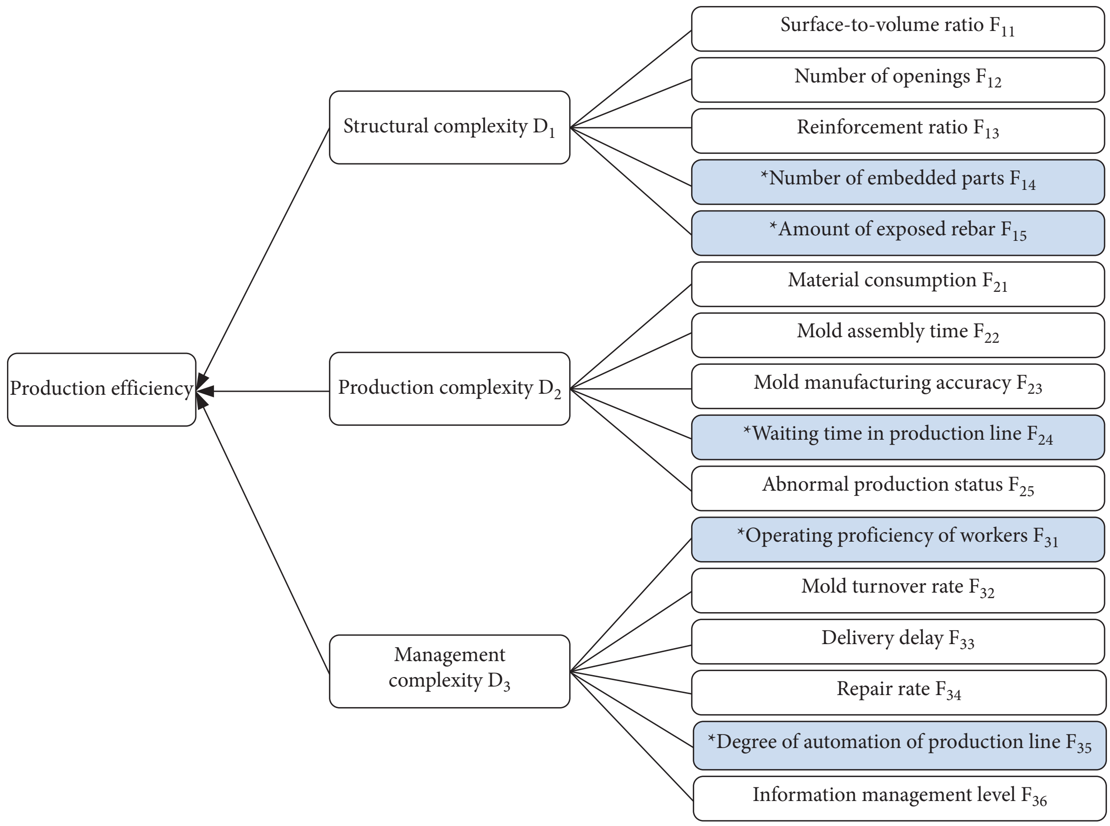

Figure 5: Relationship between complexity indices and production efficiency. Note: *denotes the top five influence complexity indices.

considerably. Therefore, to improve production efficiency from the perspective of production, the key effort should be making reasonable production scheduling plan, and a value flowchart and other technologies can be used to optimize the arrangement and reduce the waiting time in production [14].

(3) Influence of Management Complexity on Production Efficiency

It can be seen from the test results that management complexity of PC components has a significantly negative impact on production efficiency. The management of PC components is closely related to workers' activities and abilities, and advanced technical tools can help to improve labor performance.

Among the second-level complexity indices of management complexity, operating proficiency of workers and degree of automation of production line are the two that were found to have the greatest impact on production efficiency. The results reflect two typical problems in the prefabricated construction industry in China, namely, the shortage of skilled workers and the relatively low level of automation.

In China, some factories still have their mechanical equipment in an idle state and instead rely on manual operations. This leads to more error rates and less efficiency in PC component production due to the reliance on manual effort. In this context, to improve the production management level, information technology can be fully adopted to improve the automation management and information exchange in the production of PC components [48]. Moreover, industrialized production of PC components is fundamentally different from traditional construction, and there is shortage of skilled workers with the requisite expertise on key production lines. Incentive policies promoting training and increasing compensation can be used to increase the proficiency of workers and thereby improve production efficiency.

6. Conclusion

This research focused on the production management of PC components in China's offsite construction industry. A complexity index system for PC components was established, and a model representing the relationship between the complexity indices and production efficiency was built that can be used to improve the production efficiency of PC components.

First, with reference to existing research on product complexity in the machinery manufacturing industry, the concept of complexity was used as the basis for investigating the difficulty of PC component production under the given design constraints, encompassing component design complexity, component production complexity, and management complexity.

Then, following a literature review, field research, and expert interviews, a complexity index system for PC components was established using the three-stage coding method, Grounded Theory, that consisted of 3 first-level indices and 16 second-level indices. All indices are measured. The first-level indices included structural complexity, production complexity, and management complexity, while the second-level indices included surface-to-volume ratio, number of openings, reinforcement ratio, number of embedded parts, amount of exposed rebar, material consumption, mold assembly time, mold manufacturing accuracy, waiting time in the production line, abnormal production state, operating proficiency of workers, mold turnover rate, delivery delay, repair rate, degree of automation of production line, and information management level.

Finally, a model representing the relationship between complexity indices and production efficiency was built. Based on the previous work and field studies, we formulated a series of hypotheses concerning the impacts of the complexity of PC components on production efficiency. An SEM was then built based on the questionnaire survey to analyze the influence of the complexity indices of PC components on production efficiency. The results showed that the complexity index system is reliable and that the three first-level complexity indices have significant negative impacts on production efficiency. Meanwhile, the ranking of the impact weights of the 16 second-level complexity indices on production efficiency was determined. Amount of exposed rebar, waiting time in production line, degree of automation of production line, number of embedded parts, and operating proficiency of workers were identified as the top five weight indices in terms of their effect on production efficiency.

Based on the relative importance of these complexity indices in terms of their effect on production efficiency, recommendations for improving production efficiency were formulated as follows: (1) Increased standardization of PC component design should be implemented at the detailed design stage to reduce the variety of component types and reduce the structural complexity. (2) Those PC components that are not suitable for factory production, such as loading-bearing components with excessive exposed rebar, should be cast in place on site rather than being produced in an offsite PC component factory. (3) PC component manufacturing factories should apply BIM or other information technologies to assist with production management and information exchange. (4) Value flowchart and other planning technologies should be used to make production scheduling plans that reduce waiting time in the production line, especially in China, where there is significant demand for a variety of components. (5) Incentives and subsidies for worker skills training could be implemented to improve worker proficiency and to attract labor.

It should be noted that this research was subject to the following limitations: (1) The interviewees were mainly management personnel. The collected questionnaires are subject to the regions of the respondents. (2) SEM is a confirmatory analysis method, and its model construction is based on derivation of hypotheses. This research targeted the complexity of PC components for the purpose of improving production efficiency. The theoretical model was obtained through field investigation and a literature review. Other management and technical factors affecting the production efficiency of PC component production that were not considered, and other relationships between factors, can be considered in future research. (3) Grounded Theory and SEM were adopted for this research, and the key complexity indices of PC components in terms of their effect on production efficiency in PC component factories were identified accordingly. Future research can focus on establishing regression models between key complexity indices and production efficiency according to different production scenarios, as well as establishing a production simulation model to assist production management.

Data Availability

All data are listed in the submitted article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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