



Article

Interface Management Performance Assessment Framework for Sustainable Prefabricated Construction

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Abstract: Prefabricated construction (PC) has been regarded as a sustainable construction method for its inherent advantages such as energy savings, emissions reductions, and cleaner and safer working environments. However, PC development has been hindered by its inherent weaknesses of fragmentation and discontinuity. Effective interface management (IM) is regarded as integral to PC project success for its appropriate management of numerous interfaces with high complexity and uncertainty among the organization, information, and logistics. Although some researchers mentioned the effectiveness of IM for PC projects, systematic assessment methods for IM performance are missing. This study aims to systematically develop a framework to assess the IM performance of PC projects to address this gap. Through a comprehensive literature review, nineteen indicators of IM performance were identified and grouped into four categories. By combining the objective weighting method of an ordered weighted averaging (OWA) operator with the set pair analysis (SPA) method of uncertainty assessment, a nineteen-indicator assessment model was developed. Finally, a case study was constructed using the proposed framework, and the feasibility and applicability of the OWA-SPA model were proved. The assessment results provided by the assessment model could guide project managers for better IM and serve as a valuable reference for researchers in the construction industry.

Keywords: performance assessment; interface management; set pair analysis; sustainable prefabricated construction



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1. Introduction

Prefabricated construction (PC) has existed for decades [1] and aroused great interest in several countries and regions [2,3], including Japan, Germany, Malaysia, Australia, etc., because of its advantages in quality, assembly speed, cost [4], energy savings [5], emissions reductions [6], and cleaner and safer working environments [7]. In recent years, with the development and application of building information modeling (BIM), Internet of Things (IoT), and other technologies, PC has further become an important carrier of smart construction [8,9]. However, the practice of PC is still in its infancy, facing many challenges brought by the existence of geographically dispersed workplaces and having more parties involved than cast-in-situ construction [10,11]. It is critical to integrate the fragmented construction processes through proper management approaches [12].

Ideally, PC should be an organizational process with a continuity of production through a well-integrated construction organization [13]. However, the current PC processes are fragmented in a temporal-spatial distribution [14–18] with additional complexity introduced [19]. For example, compared to the traditional cast-in-situ methods, some of the works (e.g., manufacturing and preassembly of some building components, modules, and elements) are transferred to the factory for reassembly [18], leading to more new stakeholders (e.g., offsite manufacturers, transporters, and local authorities) being involved

and the complex interactions among them [19]. The functional modules of the building are decomposed into components and assembled on site after production, which adds a lot of physical interfaces that need seamless connection and actually increases the complex interface management (IM) work. Besides, the increasing complexity challenges the efficiency of information and logistics exchange during the construction process [20]. Furthermore, the PC project may face more uncertainties under the complex construction conditions due to PC technology not being mature enough and the relevant standards and specifications not being perfect [21,22]. Consequently, the success of PC relies on the collaboration of all the participants in multiple dimensions of the project management process, such as organization, technology, information, and decision making [23].

Scholars acknowledged the complexity and fragmentation of PC projects and explored different approaches to address the issues above [24–26]. Among these efforts, IM—referring to the management of information, coordination, and responsibility across physical, contractual, and organizational boundaries—was introduced to the construction industry and recognized as an effective approach to realize harmonious collaboration among project organizations [27]. IM can improve the construction processes, minimize rework, and reduce the total duration by identifying and tracing the interface or changed events [28]. For temporary construction projects, the increased transparency of IM contributes to clear and definite responsibility and authority, strict control, and organizational checks and balances [29]. Previous research also proved that IM has the potential to bring cost and time benefits during the execution of adaptive reuse building projects [30]. A case study of 45 large-scale construction projects revealed that IM practices effectively mitigate the adverse impact of project complexity originating from uncertainty in scope, communication, and large numbers of stakeholders [27]. The advantages of IM in the construction industry promote its application in PC projects. The successful experience of IM in the construction industry also provides a reference for its application in prefabricated buildings. For example, the ConBIM-IM system, which combines BIM with IM [31], can not only enhance the interface information sharing and efficiency in tracking traditional construction projects but can also optimize interface information sharing during the design, manufacturing, and installation processes of PC projects and promote better coordination among all participants. Consequently, to better cope with increased levels of PC project complexity, IM was also employed and performed well in tracking coordination between project stakeholders, overall design, logistics, external influences, and assembly processes [32]. The connection between the local component and the whole of PC building is a kind of interface. Proper IM can optimize the module design of components and provide the most concise assembly scheme [33]. The standardization of the interface between components can reduce the interdependencies between the activities for installing the building components, which are executed by different subcontractors [34]. The logistics interface between factory production and on-site installation was analyzed, and it was found that improving the IM with the aid of information technology to improve the efficiency of information transmission is useful for the integration of the construction management system [35]. BIM and lean are also being employed to improve the IM of design–production interfaces to meet a fast schedule and to overcome logistical challenges in complex PC projects [36]. A sample analysis indicated the importance of early engagement of the contractor in the design process and that open communication between all stakeholders is essential to organizational IM [37]. Accordingly, scholars believe that the performance depended on how smooth the interface could be made in PC projects [32,34,37].

Above all, IM was reported to have great potential management capabilities that need to be enhanced in PC projects [32,34]. However, as a new management method, people have limited knowledge of IM, and for this reason, how IM activities are designed or executed mainly depends on the speculation about their effectiveness. In the construction industry, most interface-management-related studies are based on traditional cast-in-situ projects or undifferentiated types of construction projects. The few PC interface-management-related studies focus on methods and strategies for interface improvement and lack an

in-depth examination of the influencing factors, let alone a quantitative evaluation of IM performance. Consequently, appropriate metrics and quantitative assessment methods are urgently needed for IM performance assessment to seek, prevent, or control the poor efficiency interfaces and continuously improve the IM performance in PC projects. To make up for the above research gap, this study aims to develop a framework to systematically assess the IM performance for PC. First, an assessment indicator system was established based on the influencing factors of IM performance that were identified through a literature review and expert interviews. Then, an ordered weighted averaging (OWA) operator was used to calculate the weights of the indicators. Moreover, a set pair analysis (SPA) was used to comprehensively assess the IM performance of PC management.

The remainder of this paper is organized as follows: Section 2 presents the literature review of performance assessment and IM. Section 3 elaborates the development of the IM performance assessment framework, covering framework design, the establishment of the IM performance assessment indicator system, and assessment method development. Section 4 uses a case study to demonstrate the proposed framework. Discussions are conducted in Section 5. Finally, the key findings, research contributions, and limitations are summarized in Section 6.

2. Literature Review

2.1. Interface Management (IM) in the Construction Industry

IM was first introduced by Wren in 1967 to deal with the complex inter-organizational interface issues within an aerospace and electric power pool project [38]. After a period of development, IM became mature and was widely used in manufacturing. With the introduction of manufacturing technology and information technology to the construction industry, IM is attracting more and more attention in construction [32,39]. The Construction Industry Institute (CII) defines IM as the “management of communications, relationships, and deliverables among two or more interface stakeholders (e.g., contractors, designers, and owners)” [40]. Although the connotation of IM is clear, its application in prefabrication is still unclear [41].

Interfaces exist where there are major discontinuities in technology, territory, time, or organization [42], resulting in significant breakpoints between activities within construction phases, for instance, between manufacture, inspection, delivery, warehousing, installation, and testing. Because of the large number and variety of activities, interfaces are generally considered highly complex and uncertain [39,42]. Due to the project’s complexity, nature variety, the multi-organizational composition of project teams, and lack of appropriate documentation procedures [43], it is a challenge to give a unified classification of interfaces. In the 1980s, organizational, managerial, and technical interfaces were identified by Morris, who put forward the corresponding IM method [38]. Pavitt and Gibb discussed the necessity of IM in the construction process and categorized the interface into physical interfaces, organizational interfaces, and contractual interfaces. From the perspective of supply chain management, the interface could be classified into the logistics interface, information interface, and management interface [37,44]. There exist other studies introducing social, functional, geographic, resource, and time interfaces [42,45].

Regardless of the different classifications of interfaces, many studies have been carried out to deepen the research of IM in several directions: (1) using IM to introduce effective communication strategies for construction project management [43]; (2) establishing error-free communication channels between different engineering specialties [46]; and (3) developing formal procedures for IM implementation [39,47].

Earlier publications have widely discussed the implication of IM and studied and presented some preliminary results, but the research related to PC projects is limited. No unified definition and classification of the interface exist. The effectiveness of IM for PC has not been investigated due to the lack of measurement criteria and evaluation methods. Appropriate metrics and a quantitative assessment method for IM performance

measurement should be proposed to set objectives, seek the shortcomings and advantages, and determine the future courses of IM improvement actions in PC projects.

2.2. Performance Assessment for IM

Performance assessment is a process to quantify the efficiency and effectiveness of individuals' or organizations' past actions [48]. Generally, it refers to the comprehensive assessment of the degrees of goal achievement and the results of implementation for achieving goals through specific statistical and scientific methods [49]. IM performance assessment assists in clarifying the efficiency of IM implementation and determining whether interfaces need to be controlled and improved [50].

As IM is a complex engineering system, it is challenging to measure IM performance: (1) many factors influence IM; (2) it is difficult to quantify the performance; (3) participants on both sides of the interface often have different understandings of the same problem; and (4) the criteria of measurement are not uniform [51]. To promote the efficiency of enterprise technological innovative IM, Xu identified four main factors (interface element composition, interface element organization, interface environment, and interface agility) that have an influence on the enterprise innovative IM and constructed a model for measuring the IM performance based on the harmonious theory [52]. Du and Liang also considered the harmonious theory as one of the references for measuring IM performance; however, a more systematic index system was established, which takes into account factors such as research and development (R&D) efficiency, communication effect, organizational structure, and cultural conflict. Based on a case study, Dong analyzed the performance of the development–manufacturing interface and found the key factors (responsibility assignment factors, information transferring factors, and enterprise culture factors) that influence IM performance [53]. Considering the complexity and multi-level characteristics of the R&D–market interface, scholars determine the hierarchical structure of IM influencing factors and determine the assessment model for IM performance based on the analytic hierarchy process (AHP) [51]. In the area of aerospace, the performance of the IM (including the mechanical, environmental, command, and data handling interfaces) process implemented by NASA between the Orion Multi-Purpose Crew Vehicle (MPCV) and the Space Launch System (SLS) was investigated through a qualitative comparison of the IM practice evidence and the criteria of the System Engineering Capability Model (SECM) [54]. In recent years, some scholars have been trying to study IM performance assessment in the construction industry. Ahn et al. collected data from 45 large-scale construction projects and analyzed the effectiveness of IM using quantitative analysis methods from the perspective of dealing with project complexity [27]. Senthilkumar and Varghese assessed the effectiveness of the implementation of a design IM system through a comparative study of two design cases of a large airport [55].

In summary, the IM performance assessment research has been extensively studied in many areas (e.g., aerospace, mechanical engineering, and technology innovation management). Although the research areas are different, researchers seem to have similar views. They all consider the factors that influence IM performance from at least three aspects: technology, organization, and information. Specific assessment methods vary from study to study, including quantitative and qualitative methods, making great progress. The achievements of these researchers are of great significance to their industries. However, IM performance assessment research in the construction industry is rarely seen. The related research has not even been touched for PC projects [56]. Learning the experiences from other areas may be helpful for the IM performance assessment of PC projects.

2.3. Methods for IM Performance Assessment

An appropriate performance assessment for IM in PC should have high applicability with the characteristics of IM. The selection of method affects the objectivity and accuracy of the assessment.

Many studies [57,58] have investigated the existing methods for performance assessment and proposed new tools to address the limitations. Fayek developed a fuzzy expert system for design project performance assessment and prediction [59]. Sun developed an assessment model based on the fuzzy AHP and TOPSIS to help industrial practitioners perform performance assessments in a fuzzy environment [58]. Chao presented a data-clustering-based fuzzy model for predicting the performance of construction projects [60]. Fullerton and Wempe used structural equation modeling (SEM) to establish the relationship between different lean tools and lean production performance [61]. Considering the IM practices and the complexity of large-scale construction projects, Shen analyzed IM performance with quantitative analysis methods, such as principal component analysis and linear regression [62].

Although the research on the performance assessment method is pervasive, few of them are designed for the IM of PC. Although the methods above consider the fuzziness and complexity of performance assessment, they cannot be directly applied to IM performance assessment because the fragment-integration organization characteristics of PC make the IM of different participants, different construction processes, and entity interfaces a complex uncertainty system. Determining how to deal with the uncertainty of IM performance assessment is the motivation for this study. Although the fuzzy assessment method can deal with uncertainties to some extent [63], it has a few limitations. For example, after quantifying the indicators with the fuzzy assessment method, it is easy to ignore that different impact factors at the same performance level may have considerable differences [64]. In order to embody this difference as vividly as possible, it is necessary to accurately grasp the unity of opposites between certainties and uncertainties and make full use of the assessment information [64]. As a modern uncertainty theory that overlaps the other uncertainty theories such as probability, vague, rough, and fuzzy theory [65], set pair analysis (SPA) regards certainties and uncertainties as an integrated certain–uncertain system [66]. It takes full account of the relationship between impact factors and the performance scale to more comprehensively determine the subordinate degree of the factors to performance scale [67]. Compared to the traditional assessment methods, it can not only improve the accuracy of performance assessment by making full use of assessment information but it can also predict the trend of performance development by analyzing the relationship between factors and different scales. This advantage of the SPA model will help managers make more forward-looking decisions in the IM practices for PC.

It is also indispensable to the weight of each performance indicator in the assessment process. The rationality of the indicator weight calculation is critical to ensure the accuracy of assessment results [68]. The traditional weighting method is usually based on the direct calculation of the weights given by experts [69]. However, some experts may assign weights that deviate from reality due to subjective reasons [14]. An ordered weighted averaging (OWA) operator, an objective weighting method, can significantly reduce the adverse effects caused by extreme values of decision data and make the weights more objective and reasonable [69]. OWA has been widely used in environmental assessment [70], strategic decision [71], risk assessment [72], and performance assessment [73]. In this paper, the combination of an OWA operator and SPA is adopted to reflect all data information objectively in the assessment results.

3. Development of IM Performance Assessment Framework

This section aims to develop a framework for assessing the IM performance of PC projects. The framework development can be divided into three stages (Figure 1): (1) identify the major indicators that affect IM (Section 3.1) to establish an IM performance assessment indicator system; (2) invite experts to analyze the importance of indicators to determine their weights based on OWA operator (Section 3.2); and (3) calculate the single-indicator connection degree and synthetic connection degree based on SPA (Section 3.3).

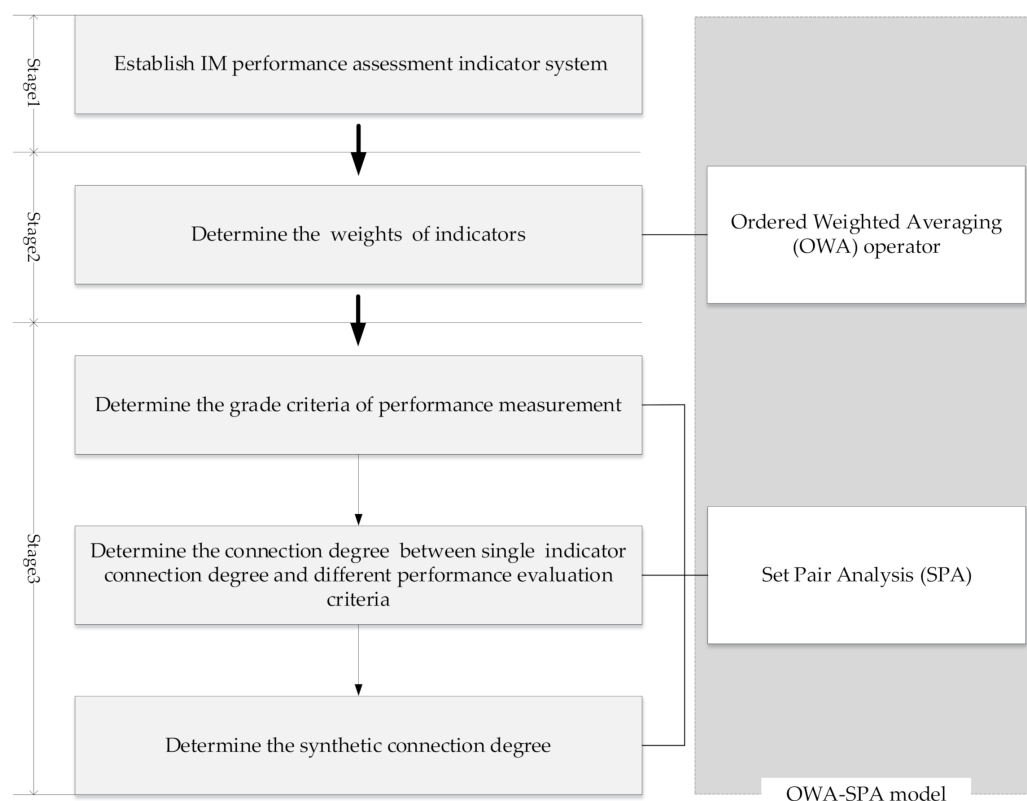


Figure 1. The research flow for model development.

3.1. Establishment of IM Performance Assessment Indicator System

Existing studies indicate that PC has more interfaces to be managed and that IM is more complicated and more critical than in cast-in-situ construction [74]. Although many studies [32,37,75,76] focus on the strategy of improving IM, a systematic performance analysis for IM has not been carried out. An indicator system is a prerequisite for an IM performance assessment. Therefore, this study first conducted a literature survey to identify nineteen indicators (Table 1) affecting IM performance and categorized them into four groups according to the following interfaces: the physical interface (I_1), information interface (I_2), relational interface (I_3), and logistics interface (I_4). The indicators could be revised and customized according to the characteristics of specific projects.

- (1) The physical interface refers to the actual, physical connections between two or more building components [32]. The common problems of weather-tightness, tolerance/fit, and constructability of PC projects are usually due to the failure of physical interfaces [32]. For prefabricated buildings, functional modules are decomposed into smaller components, which can meet the requirements of high-efficiency factory production [77]. However, the increase of the type and quantity of components greatly increases the complexity of the physical interfaces between components, which leads to the challenge of physical IM [34]. They challenge the design, manufacture, and construction and even the whole life cycle stage of PC projects [32]. The number and complexity of physical interfaces are largely determined by the building's detailed design [32]. Designing standardized interfaces can reduce the complexity of the interface and promote the interoperability of different disciplines at the interface, which consequently reduces the interdependencies between the activities for installing the building components [34,78,79]. Standardization is also considered to facilitate the implementation of modular coordination as a rule for the configuration of physical interfaces [80]. Inaccurate and nonstandard design is considered to be the main factor affecting the compatibility of building components [81]. Although the interface is not mentioned here, the compatibility between components reflects the performance of

the physical interface. It is a great challenge for designers to meet the requirements of physical interface performance by ensuring the accuracy of design because it is difficult to accommodate the movement and tolerance of each component and still maintain the integrity of the building [32]. Pavitt and Gibb describe the complexity of physical interfaces with an example that shows a typical physical interface between two cladding types [32]. Complexity in terms of numerous different components and the range of different interconnections between components can bring out difficulties for matching components to another [37]. Chen et al. found that the complexity of physical interfaces makes it easy to conflict when matching various components, which usually reduces constructability [76]. PC projects have strict tolerance requirements to prevent mismatching during component assembly [82], which puts forward high precision control requirements. For this reason, a dimensional and surface quality assessment of a precast concrete elements method was developed based on BIM and 3D laser scanning [83–85]. Besides, due to the high installation precision that is required (i.e., with small construction tolerances), risks, such as sealing joints, might come along with the assembly of prefabricated components [86]. Therefore, the accuracy of the completed working surface is the guarantee of PC projects [86]. Glass and Pepper cited practical concerns regarding ‘physical joints and interfaces’, focusing on the need for high levels of technology to ensure sufficient weatherproofing, particularly around windows [16]. Subsequently, the reliability of component interface connection technology has been one of the critical issues for PC projects [74,87].

- (2) The information interface is the basic interface among almost all kinds of interfaces. It is important for carrying the motivation, consciousness, emotion, and knowledge of both sides [88]. Unlike the physical interface, the information interface is invisible, but the transmission and interaction of information at the interface are real. Ensuring the effectiveness of information transmission and interaction at the interface is critical for the implementation of tasks. Sacks et al. emphasize the importance of exchanging information between installation and fabrication [89]. BIM is also a good example, which is committed to breaking the delay, omission, and asymmetry of information in the interface through a standardized information model [9,90]. The process design, manufacture, and construction of PC projects are located in different sites and require highly continuous information exchange among all stakeholders to achieve project success [91]. A professional information management system is recommended to be used in PC projects to manage interface-related information [4]. Transmitting and storing information in a standardized way is the basis for different stakeholders to share project information and interoperate in their information management systems [92]. The lack of information standards lowers the quality of information generated and reduces the communication efficiency and subsequent application [76]. Considering that the project information is transmitted between two or more geographically dispersed stakeholders [4], the receiving party may exaggerate or distort the subjective judgment of the information before transmitting it to other participants [93]. Therefore, managers should pay more attention to the distortion of information transmitted at the interface. Information sharing has been highly valued in the whole construction industry (both traditional construction projects and PC projects). Traditionally, the main methods for dealing with information interfaces in projects were the sharing of drawings and specifications, face-to-face meetings, oral presentations, phone conversations, and emails [27]. With the development of information technology, the information interface has been improved greatly. Advanced technologies such as RFID and BIM have been used to improve the degree of information sharing [94–96]. In addition to the challenges in the process of information transmission and storage, the expression defects of early design information make it difficult for manufacturers and constructors to use the design information when they receive it [97]. The lack of effective information integration processes also makes the information stored in paper and existing in the designer’s brain difficult to produce reuse value [97]. As the

PC projects are difficult to change after the components are installed, the stakeholders (e.g., designers, manufactures, and constructors) of PC projects are advocated to intervene in the design stage early so that the design is oriented to manufacturing and installation at the beginning [23,37]. Meanwhile, the current information integration technology meets the high level of design information integration [90].

- (3) The relational interface refers to the interaction interface between geographically dispersed stakeholders, which can also be called the organizational interface [37]. Clarity of contract responsibility, power, and interest of contract is a formal guarantee to maintain the complex interface relationship among the designer, manufacturer, constructor, and other parties [32,35]. Direct evidence is an increase in the use and importance of contracts to govern relationships and enforcement of the terms of agreements [47]. Considering that a PC project is a typical temporary organization of geographically distributed stakeholders who have different working cultures [98], interface participants need to share a common culture. Otherwise, cultural differences may lead to a series of problems of information sharing, communication, and even cooperative attitudes, which will affect the performance of the relationship interface [99,100]. Making the goal consistent is the original intention of the contract and the beginning of a harmonious informal relationship. The existing IM-related research emphasizes that the commitment to a common goal can mitigate the complicated interaction at the interface [47]. Specifically, goal consistency is more essential for the IM of the PC projects where there are many geographically dispersed stakeholders [32,101]. Further, the cooperation attitudes of participants cannot be ignored. Some studies have found that organizations with a strong willingness to cooperate are more likely to enhance the relationship strength than those with a poor willingness [98], which can maintain better interface performance. In PC projects, participants are encouraged to participate in design and production planning through early cooperation as much as possible [2,101]. However, poor cooperation between the participants during the early stage is often caused by insufficient or inadequate communication [32]. McCarney and Gibb regards effective communication as one of the key factors affecting the IM of PC projects [101].
- (4) The logistics interface mainly exists between the manufacturing plant and the installation site, which is the key to ensure the seamless connection between the component production and site assembly/installation. However, the space constraints for storage and traffic congestion still restrict the smooth delivery of components. The lack of just-in-time (JIT) delivery was identified as a critical risk in PC projects [102]. Strengthening the research on JIT in PC projects may significantly improve the performance of the logistics interface. While ensuring on-time delivery, the quality assurance component at the logistics interface also needs to be guaranteed. Due to the large size, the prefabricated components are prone to damage during transportation [103,104]. The resulting rework problems may lead to severe delays in downstream work. Further, the order and position of prefabricated components are well-organized, so the logistics interface between manufacturing and on-site installation needs to be well-tracked [102]. Recently, auto-ID technologies, such as barcode and RFID, were developed for this work [102,105,106].

Given the limited research literature on IM in PC projects, we have consulted almost all the relevant literature of PC so far to find indicators, but this still cannot guarantee comprehensiveness. Therefore, we draw lessons from the experience of some traditional construction project IM research. For the indicators that are suitable for PC projects but not yet explored in this field, they are also selected as the factors influencing the IM performance of PC projects with the approval of experts in the field. For example, “distortion of information in transmission”, which has only been verified in EPC project IM research, is also an important factor in PC projects.

Table 1. IM performance assessment indicator system of PC projects.

First-Level Indicators	Second-Level Indicators	Sources of References
Physical interface (I_1)	Design standardization degree (I_{11})	[32,34,37,78–80]
	Design accuracy (I_{12})	[32,37,81]
	Complexity of physical interfaces (I_{13})	[16,32,75,76,107]
	Standardization degree of process interface (I_{14})	[37,39,42]
	Precision control of component manufacturing (I_{15})	[82,84,85]
	Accuracy of completed working surface (I_{16})	[79,86]
	Reliability of component interface connection technology (I_{17})	[16,19,37,74,87]
Information interface (I_2)	Standardization of information transmission and storage (I_{21})	[4,47,76,91,92]
	Distortion of information in transmission (I_{22})	[93]
	Degree of information sharing (I_{23})	[27,39,47,96,102]
	Integrity and accuracy of design information (I_{24})	[90,97]
Relational interface (I_3)	Clarity of contract responsibility, power, and interest (I_{31})	[32,35,36,75]
	Goal consistency (I_{32})	[32,47,62]
	Inter-organizational cultural differences (I_{33})	[99,100,102]
	Cooperation attitude of participants (I_{34})	[16,76,98,102]
	Effective communication between participants (I_{35})	[10,32,101]
Logistics interface (I_4)	On-time delivery of components to the site (I_{41})	[14,44,102,108]
	Component quality assurance in transportation process (I_{42})	[103,104,108]
	Tracking of components in the transportation process (I_{43})	[102,105,106,108]

3.2. Calculation of the Weights for the Indicators Based on OWA Operator

Ordered weighted averaging (OWA) was first introduced by Yager in 1988 [109]. This method weakens the adverse effects of extreme values by re-aggregating data sequences and differentiating the weighted data. Its essence lies in the incremental arrangement of data, and the weight is only related to its location [66]. Various OWA operators have been proposed for improving the form of data aggregation [110,111]. In this study, the classical OWA operators are improved by using a combination number as a weighting vector for data aggregation, weighting decision data by the combination number, and calculating the weight of each indicator [112]. The detailed steps for weight calculation are elaborated as follows:

- (1) The importance scores $(a_1, a_2, \dots, a_i, \dots, a_n)$ of the indicators are sorted in descending order, and the sequence of decision data becomes $B = (b_0, b_1, \dots, b_i, \dots, b_{n-1})$, where $b_0 \geq b_1 \geq \dots \geq b_i \geq \dots \geq b_{n-1}$.
- (2) Calculate the weight of b_j by the number of combinations:

$$w_{j+1} = \frac{C_{n-1}^j}{\sum_{k=0}^{n-1} C_{n-1}^k} = \frac{C_{n-1}^j}{2^{n-1}}, j = 0, 1, 2, \dots, n-1 \quad (1)$$

where C_{n-1}^j is the number of possible j objects from a set of $n-1$ objects.

- (3) The weighted vector, w , is used to weigh the decision data, B , to calculate the absolute weight, \bar{w}_i , of the indicator:

$$\bar{w}_i = \sum_{j=1}^n w_j \cdot b_j, w \in [0, 1], j \in [1, n] \quad (2)$$

- (4) Calculation of the relative weight of the indicator:

$$\omega_i = \frac{\bar{\omega}_i}{\sum_{i=1}^m \bar{\omega}_i}, i = 1, 2, \dots, m \quad (3)$$

The weight determination of the indicator system can be accomplished by repeating the above steps.

3.3. IM Performance Assessment Based on SPA

Set pair analysis (SPA) was proposed to describe and process the system uncertainty [68]. The core idea is to treat the problem of certainties and uncertainties as an integrated certain–uncertain system by analyzing the uncertainties of the system from three aspects: identity, discrepant, and contrary [113]. Its basic concepts are set pair and connection degree. A set pair, $H(A, B)$, is a pair combined with two dependent sets, A and B . The connection degree is a connection number determined by the identity degree, discrepancy degree, and contrary degree for set A and B under certain circumstances [66]. Therefore, the key to SPA is to calculate the connection degree of the two sets. Suppose there are N elements in set pair $H(A, B)$. To show its total features, S elements show the identity features, and P elements show the contrary features, such that $F = N - S - P$ shows the discrepant features. Then the connection degree number (μ) is represented as follows:

$$\mu = a + b\alpha + c\beta \quad (4)$$

where $a = S/N$, $b = F/N$, and $c = P/N$ denote the identity degree, discrepancy degree, and contrary degree, respectively, and $0 \leq a, b, c \leq 1$ and $a + b + c = 1$; and $i \in [-1, 1]$ and $j = -1$ are the coefficients of discrepancy degree and contrary degree, respectively.

For the sake of understanding, the basic principle of SPA is rough, only dividing the state-space of a research object into three, which may not be directly applied to more complicated problems. Thus, it is necessary to expand Equation (4) on different levels to form a kind of multivariate connection degree [113]. The multivariate connection degree can be achieved as follows:

$$\mu = a + b_1\alpha_1 + b_2\alpha_2 + \dots + b_k\alpha_k + c\beta \quad (5)$$

where b_1, b_2, \dots, b_k are the components of discrepancy degree, representing the grades of discrepancy degree (e.g., mild discrepancy, discrepancy, and severe discrepancy); $\alpha_1, \alpha_2, \dots, \alpha_k$ are the coefficients of components; and, obviously, $a + b_1 + b_2 + \dots + b_k + c = 1$.

The connection degree describes the relationship between certainties and uncertainties. Considering the complexity of IM and the variability of the external environment, assessing IM performance based on the SPA can deal with the uncertainty of decision information more pertinently and effectively. The method has three steps as follows.

3.3.1. Determination of the Performance Measurement Scales

Before the SPA is used for quantitative assessment of the qualitative indicators, the measurement scales for each indicator's performance are needed [114]. In general, the measurement scales are divided equally according to statistical principles [115]. However, some scholars try to further improve the scientificity of evaluation by adjusting the measurement scale of different grades. For example, Chen et al. proposed a fuzzy interval by reducing the measurement scale of high grades and expanding the measurement scale of low grades [112]. Accordingly, this paper defined four scales for the performance measurement for implementing SPA and IM performance assessment: poor, fair, good, and excellent, as summarized in Table 2. Then, the experts can assign corresponding scores according to their judgment as decision-making data in the assessment process.

Table 2. The scales for performance measurement.

Scale	Semantics	Score Interval
G_1	poor	[0, 5]
G_2	fair	(5, 7]
G_3	good	(7, 9]
G_4	excellent	(9, 10]

3.3.2. Calculation of Single-Indicator Connection Degree

Determining the IM performance connection degree of each performance indicator is the key for SPA application. Therefore, in the process of performance assessment, the first stage is to calculate the single-indicator connection degree between each IM performance indicator and each scale of performance measurement [113]. The specific steps are described as follows:

- (1) Experts are invited to score the performance of each indicator in the 2nd level, according to Table 2. The initial performance score of the indicator can be obtained by averaging the scores from the expert group. Qualified experts shall be scholars or engineers/managers with extensive working experience in the field of PC.
- (2) The initial performance scores of each indicator are paired with different performance scales ($G_k, k = 1, 2, 3, 4$) and are regarded as a set pair, represented by $\mu(x_{ij}, G_k)$ for the second-level indicator x_{ij} . Then, the single-indicator connection degree between G_k and x_{ij} can be calculated in light of the following rules: μ_{ijk} represents the single-indicator connection degree between sample indicator x_{ij} and G_k . The identity is considered when x_{ij} falls in G_k ($\mu_{ijk} = 1$); the discrepant is considered when x_{ij} falls in the proximity of G_k ($\mu_{ijk} = [-1, 1]$); and the contrary is considered when x_{ij} falls in another scale ($\mu_{ijk} = -1$). μ_{ijk} can be calculated as follows [113]:

$$\begin{aligned}
 \mu_{ij1} &= \begin{cases} 1, & x_{ij} \leq s_1 \\ 1 - 2(x_{ij} - s_1)/(s_2 - s_1), & s_1 \leq x_{ij} \leq s_2 \\ -1, & x_{ij} \geq s_2 \end{cases} \\
 \mu_{ij2} &= \begin{cases} 1 - 2(s_1 - x_{ij})/(s_1 - s_0), & x_{ij} \leq s_1 \\ 1, & s_1 \leq x_{ij} \leq s_2 \\ 1 - 2(x_{ij} - s_2)/(s_3 - s_2), & s_2 \leq x_{ij} \leq s_3 \\ -1, & x_{ij} \geq s_3 \end{cases} \\
 \mu_{ij3} &= \begin{cases} -1, & x_{ij} \leq s_1 \\ 1 - 2(s_2 - x_{ij})/(s_2 - s_1), & s_1 \leq x_{ij} \leq s_2 \\ 1, & s_2 \leq x_{ij} \leq s_3 \\ 1 - 2(x_{ij} - s_3)/(s_4 - s_3), & x_{ij} \geq s_3 \end{cases} \\
 \mu_{ij4} &= \begin{cases} -1, & x_{ij} \leq s_2 \\ 1 - 2(s_3 - x_{ij})/(s_3 - s_2), & s_2 \leq x_{ij} \leq s_3 \\ 1, & x_{ij} \geq s_3 \end{cases}
 \end{aligned} \tag{6}$$

where $s_k (k \geq 1)$ is the upper limit of the score interval for G_k , and s_k is the lower limit of the score interval for G_1 .

After the calculation, the single connection degree between G_k and each IM performance indicator can be obtained. Taking the second-level indicator matrix $\{x_{1j} | j = 1, 2, 3, \dots, m\}$ under the first-level indicator x_1 as an example, we can obtain the connection degree (μ_{1jk}) between each second-level indicator and G_k , as shown in Table 3.

Table 3. Calculation of single-indicator connection degree.

Indicators	G_1	G_2	G_3	G_4
x_{11}	μ_{111}	μ_{112}	μ_{113}	μ_{114}
x_{12}	μ_{121}	μ_{122}	μ_{123}	μ_{124}
x_{13}	μ_{131}	μ_{132}	μ_{133}	μ_{134}
...
x_{1m}	μ_{1m1}	μ_{1m2}	μ_{1m3}	μ_{1m4}

3.3.3. Calculation of Synthetic Connection Degree

In calculating the synthetic connection degree, the criteria of the identity, discrepant, and contrary judgments of SPA should be obeyed as well. When the indicator falls in G_k , the identity is considered; when the indicator is adjacent to G_k , the discrepant is considered; and when the indicator is in the other scales, the contrary is considered.

Taking $\mu(x_1, G_1)$ for x_1 at the first level as an example, assume that the total number of second-level indicators under x_1 is m . Among those m second-level indicators, s second-level indicators fall in G_1 , with the corresponding weights of each indicator as c_1, c_2, \dots, c_s , f second-level indicators are adjacent to G_1 , with the corresponding weights of each indicator as d_1, d_2, \dots, d_f , and p second-level indicators fall in scales other than G_1 , with the corresponding weights of each indicator as e_1, e_2, \dots, e_p . Therefore, $s + f + p = m$. The connection degree can be calculated using Equation (7):

$$\mu(x_1, G_1) = \sum_{h=1}^s c_h + \sum_{k=1}^f d_k \alpha_k + \sum_{l=1}^p e_l \beta_l \quad (7)$$

where α_k is the single-indicator connection degree between each indicator x_{1k} and G_2 , and β_l is the single-indicator connection degree between each indicator and G_3/G_4 . As the connection degree of the same scale is 1 and the connection degree of the different scale is -1 , Equation (7) can be simplified as:

$$\mu(x_1, G_1) = \sum_{j=1}^m \omega_{ij} \mu_{ijk} \quad (8)$$

Among the equations, ω_{ij} is the weight of each second-level indicator under the first-level indicator x_1 , m is the number of the indicators under x_1 , and μ_{ijk} is the connection degree.

Similarly, the degrees of association between x_1 and other scales (G_2, G_3 , and G_4) can be calculated according to Equation (8).

Finally, according to the principle of maximum connection degree [64], the maximum connection degree of the IM performance is as follows:

$$\mu(x_1, G_q) = \max\{\mu(x_1, G_k), k = 1, 2, 3, 4\} \quad (9)$$

Therefore, the IM performance scale of x_1 is G_q .

4. Case Study

To demonstrate the application of the proposed OWA-SPA model, a PC project is analyzed using the proposed model.

4.1. Project Background

The project is located in a megacity in South China, with five residential towers, 51–53 floors above ground and three floors underground. The completed project can accommodate 1760 households with a gross floor area of 150,000 square meters. The pre-fabricated components used in the project cover facades, stairs, and interior wall panels. The assembly rate is approximately 55%. The assembly of a large number and a variety of prefabricated components forms complex physical interfaces. To achieve the project

objectives, seven major stakeholders from different disciplines participate in the project, e.g., client, designer, component designer, general contractor, consultant, and two manufacturers (manufacturer A and manufacturer B). The construction process is geographically fragmented. Three sites participate in the construction process. The prefabricated components are produced by those two different offsite manufacturers and transported to the construction site for installation. To ensure that the interfaces of the components produced by the two manufacturers can match seamlessly during installation and can be delivered to the site on time, a high degree of collaborative work among manufacturer A, manufacturer B, and the general contractor is the guarantee of project implementation. In addition to direct construction tasks, the flow and interaction of resources and information among the seven independent participants constitute more complex rational and information interfaces. According to the distance measurement of the three sites, the distances between the two component factories and the site are 45 km and 40 km, respectively. Due to the uncertainty of transportation conditions and high requirements of component protection, the logistics interfaces between the factory and the site are challenged.

In order to achieve the project objectives, some advanced technologies and management methods were adopted, many of which are effective for improving IM performance. For example, BIM is used in the project, and a large number of physical interface problems (more than ten interface conflicts between the ventilation ducts and the lintel and more than fifty physical interface conflicts between the precast partition seam and the electromechanical point) are found before the project construction. The standardized design method is adopted. The prefabricated component size is designed according to the principle of less specification and more combination. The physical interface between components has been designed as standardized as possible, which follows the requirements of safety, economy, and construction convenience. However, most physical interface connections still need to be performed by manual wet operation, and any change may cause large-scale rework. In the construction site, most of the installation procedures are also strictly standardized. The installation of prefabricated wall panels and stairs is broken down into several work packages that need to be strictly implemented. The finished wall column shall be checked for levelness and flatness, which provides a good interface environment for the follow-up work. Further, quick response code (QR code) technology was adopted in the delivery and transportation of components for tracking components in the process of transportation. The adoption of this technology, to a certain extent, promotes cooperation between the manufacturers and the construction site and improves the performance of the logistics interface.

It should be noted that the developers of this project rank in the top five among the real estate enterprises in China, sometimes even the first. The other participants in the project are all top enterprises in China, representing the highest level of PC in China. By assessing the IM performance of this project, some problems of PC in China can be revealed to a certain extent.

4.2. Data Collection

A group of six experts was invited to rate the importance of all indicators. The profiles of those experts are summarized in Table 4. Similar to Cong and Ma's study (2018), the importance scores of indicators have values from 0 to 5, and the interval range is divided to determine the degree of the importance ([0, 1) = not important at all, [1, 2) = of little importance, [2, 3) = of average importance, [3, 4) = very important, [4, 5) = absolutely essential). For the sake of simplicity, all scores were taken as an integer multiple of 0.5, e.g., 1, 2.5, and 5. The second-level indicators U_{21} , U_{22} , U_{23} , and U_{24} under U_2 are used as examples to show the importance scores of these indicators, as shown in Table 5. E_{11} , E_{12} , E_{13} , E_{14} , E_{15} , and E_{16} represent the six experts invited. Note that the measurement of the importance of indicators depends on the rich knowledge and experience of experts in this field. Academic professionals often have a deep understanding of the knowledge system and have experience in participating in investigation and research. Therefore, three

of the six experts invited for weight determination are academic professionals. One of them has more than 20 years of experience in the field of PC research, participated in dozens of national projects, and cooperated with numerous enterprises in development projects.

Table 4. Profile of the experts invited to weight the indicators.

Interviewee NO.	Position	Years of Working Experience Related to PC
1	Professor	10
2	Professor	21
3	Associate Professor	7
4	Senior engineer from a private developer	5
5	A chief manager from a private contractor	8
6	A senior structural engineer from a design institute	7

Table 5. The importance score of U_{21} , U_{22} , U_{23} , and U_{24} .

	E_{11}	E_{12}	E_{13}	E_{14}	E_{15}	E_{16}
U_{21}	4	4.5	4	4.5	4.5	4.5
U_{22}	2	3.5	4	4	4	4.5
U_{23}	3.5	3.5	3.5	5	4.5	4.5
U_{24}	4	4.5	4.5	4.5	4	4

In order to collect the data used for calculating the connection degree, another group of six experts were invited to assess the performance of all the second-level indicators, and their engineering practice experiences were focused. The profile of the experts is shown in Table 6.

Table 6. Profile of the experts invited to access the performance of all the second-level indicators.

Interviewee NO.	Title	Represented Stakeholder in the Project	Familiarity with the Project	Years of Working Experience
1	Associate Professor	Consultant	Familiar	7
2	Project manager	Client	Very familiar	6
3	Senior engineer	Main contractor	Very familiar	15
4	Project manager	Main contractor	Very familiar	5
5	Design manager	Design consultant	Very familiar	9
6	Consulting engineer	Supervision Company	Very familiar	4

4.3. Identification of Critical Factors and Establishment of Indicator System Based on Engineering Practice

To ensure the applicability of the indicator system to the project, four practitioners working on this residential construction project were invited to review the indicator system. This group of practitioners includes a general project manager from the client, a project manager, a site manager, and a design manager. The practitioners generally agreed with the indicator system established in this paper but made some amendments. The practitioners believed that the “distortion of information in transmission” is mainly affected by the degree of information standardization and sharing. There is no need to include this indicator in the indicator system as “standardization of information transmission and storage” (I_{21}) and “degree of information sharing” (I_{23}) are already included. Besides, the timeliness of information transmission is indeed an important indicator that was ignored by the original indicator system. Therefore, the “distortion of information in transmission” was replaced by “timeliness of information” (I_{22}). “quality assurance of parts in transportation process” was considered to have little impact on the overall logistics interface of the project, mainly affecting on-site assembly work. Therefore, the indicator “quality assurance of parts in

transportation process” was removed. The revised IM performance indicator system for the project is presented in Figure 2.

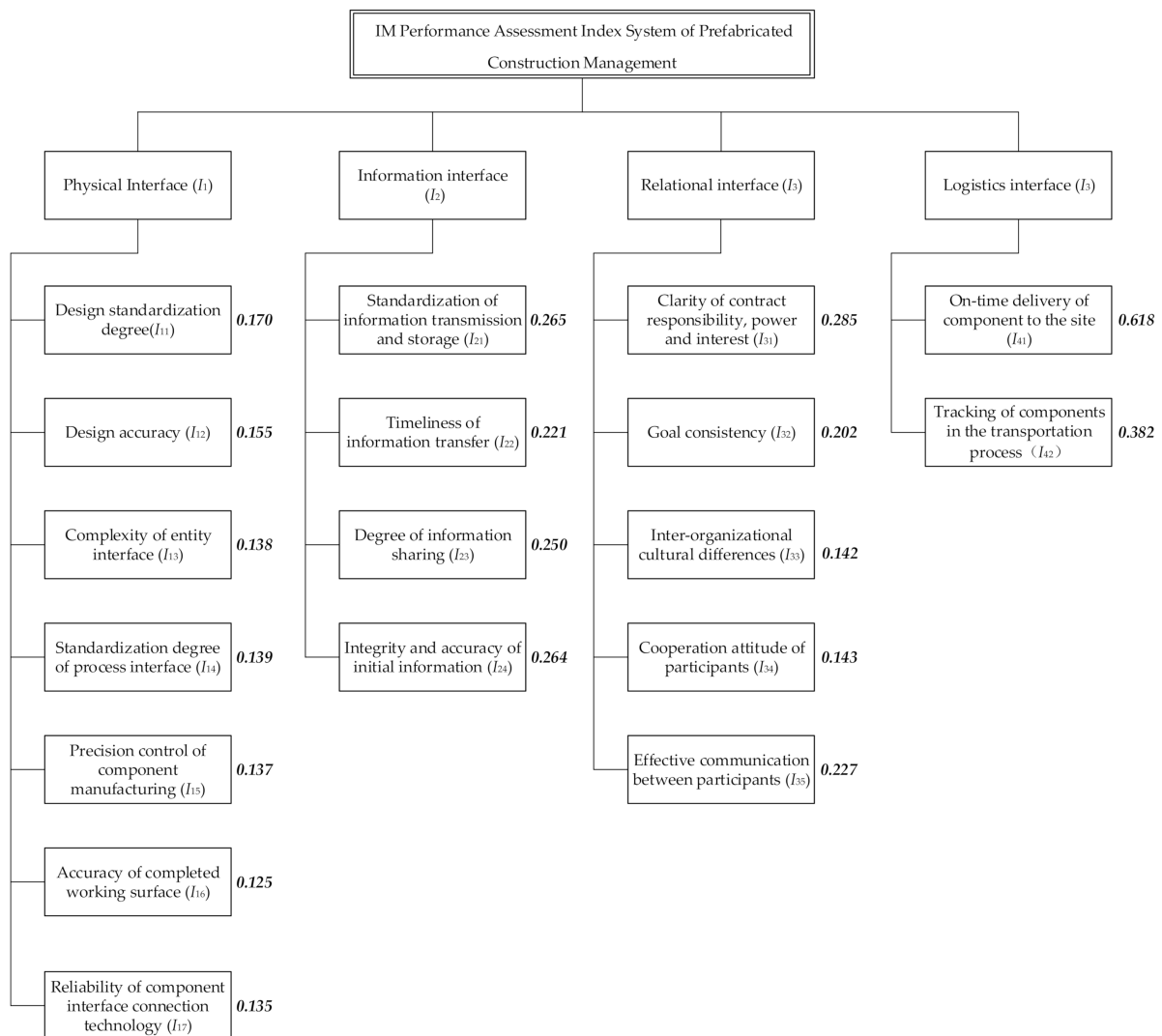


Figure 2. Indicators factors affecting IM performance with local weights.

4.4. Application of the OWA-SPA Model

4.4.1. Calculation of Weights for Indicators

The importance score assigned by experts was used to calculate the weights of second-level indicators according to the OWA operator described in Section 3.2. The weights of all the second-level indicators are shown in Figure 2.

4.4.2. Calculation of Single-Indicator and Synthetic Connection Degrees

Based on the data collected from experts, the initial performance score of the second-level indicators was obtained by averaging the experts' scores, as shown in Table 7. E_{21} , E_{22} , E_{23} , E_{24} , E_{25} , and E_{26} represent the six invited experts.

According to the scale of performance measurement and Equation (6), the single-indicator connection degrees of IM performance indicators were calculated. Then, the scale of each IM performance indicator was determined according to the principle of maximum connection degree. The results are summarized in Table 8.

Table 7. The initial performance scores of the IM performance indicators.

	E_{21}	E_{22}	E_{23}	E_{24}	E_{25}	E_{26}	Average Score
I_{11}	1	3.5	3.5	3	3.5	3	2.92
I_{12}	5	7	6.5	6	6.5	6	6.17
I_{13}	4.5	3	5	3	3	4.5	3.83
I_{14}	5	6	5	5.5	5.5	4	5.17
I_{15}	9	8	8.5	8	9	8.5	8.50
I_{16}	7.5	6.5	7.5	8	7	7.5	7.33
I_{17}	4.5	7	6	6.5	6	6	6.00
I_{21}	5.5	5.5	6	4	6.5	5.5	5.50
I_{22}	7.5	7	6.5	7	7.5	7	7.08
I_{23}	7	6.5	7	5.5	7	6.5	6.58
I_{24}	7.5	7	7	6.5	7.5	7	7.08
I_{31}	7	6.5	6.5	5	6	5.5	6.08
I_{32}	6	6	5.5	6	5	5.5	5.67
I_{33}	6.5	5.5	6	5	5.5	6	5.75
I_{34}	8	7	7.5	8	8	7.5	7.67
I_{35}	5.5	6.5	5	5.5	5	7.5	5.83
I_{41}	6	5.5	4	5	5.5	4.5	5.08
I_{42}	7	7.5	6.5	8	7.5	7.5	7.33

Table 8. The single-indicator connection degree of IM performance indicators.

	G_1	G_2	G_3	G_4	Performance Scale
I_{11}	1.000	0.167	-1.000	-1.000	G_1
I_{12}	-0.167	1.000	0.167	-1.000	G_2
I_{13}	1.000	0.533	-1.000	-1.000	G_1
I_{14}	0.833	1.000	-0.833	-1.000	G_2
I_{15}	-1.000	-0.500	1.000	0.500	G_3
I_{16}	-1.000	0.667	1.000	-0.667	G_3
I_{17}	0.000	1.000	0.000	-1.000	G_2
I_{21}	0.500	1.000	-0.500	-1.000	G_2
I_{22}	-1.000	0.917	1.000	-0.917	G_3
I_{23}	-0.583	1.000	0.583	-1.000	G_2
I_{24}	-1.000	0.917	1.000	-0.917	G_3
I_{31}	-0.083	1.000	0.083	-1.000	G_2
I_{32}	0.333	1.000	-0.333	-1.000	G_2
I_{33}	0.250	1.000	-0.250	-1.000	G_2
I_{34}	-1.000	0.330	1.000	-0.333	G_3
I_{35}	0.167	1.000	-0.167	-1.000	G_2
I_{41}	0.917	1.000	-0.917	-1.000	G_2
I_{42}	-1.000	0.670	1.000	-0.667	G_3

According to the weight of each indicator and the single-indicator connection degree of the IM performance indicators, the synthetic connection degree of each first-level indicator was obtained using Equation (8), shown in Table 9.

Table 9. The synthetic connection degree of each first-level indicator.

	G_1	G_2	G_3	G_4	Performance Scale
I_1	0.136	0.546	-0.136	-0.752	G_2
I_2	-0.498	0.960	0.498	-0.960	G_2
I_3	-0.026	0.903	0.026	-0.903	G_2
I_4	0.185	0.874	-0.185	-0.874	G_2

4.5. Results

As shown in Table 9, the performance of all indicators at the first level is rated as fair. Although the performance of the “physical interface” (I_1) is described as “fair”, its connection degree with G_2 is relatively low compared to the connection degrees of the other three interfaces. Therefore, it is necessary to look into the single-indicator connection degrees of the second-level indicators under the “physical interface” (I_1). According to Table 8, two second-level indicators (I_{11} and I_{13}) fall in G_1 (Poor), three second-level indicators (I_{12} , I_{14} , and I_{17}) fall in G_2 (Fair), and the remaining two second-level indicators (I_{15} and I_{16}) fall in G_3 (Good). The performance of those seven indicators is relatively dispersed, resulting in the low connection degree between the “physical interface” and G_2 . Although the performance of “precision control of component manufacturing” (I_{15}) and “accuracy of completed working surface” (I_{16}) is good, the performance of the “physical interface” is still fair because of the poor performance of “design standardization degree” (I_{11}) and “complexity of entity interfaces” (I_{13}).

The performance of the “information interface” (I_2) is rated as fair for its high connection degree with G_2 . However, the high connection degree with G_3 should not be ignored. According to the single connection degrees shown in Table 8, all four indicators under the “information interface” show a high connection degree with G_2 ; “timeliness of information in transmission” (I_{22}), “degree of information sharing” (I_{23}), and “integrity and accuracy of design information” (I_{24}) show high connection degrees with G_3 . These indicate that the performance level of the “information interface” at “fair” has the possibility of moving to the next level of “good”. “standardization of information transmission and storage” (I_{21}) shows the worst performance, which is the weak point of the information interface.

The “relational interface” (I_3) is a reflection of the actual cooperative action between the participants at the interface and has a significant impact on the physical interface, information interface, and logistics interface. However, as shown in Table 9, its high connection with G_2 reveals a “fair” performance level, and the low connection degree with other scales indicates a certain degree of stability. Therefore, it is unlikely to move from “fair” to “good” or “poor” for the performance of the “relational interface”. The connection degrees of subordinate indicators (I_{32} , I_{33} , and I_{35}) with G_2 confirm the above analysis. Nevertheless, “initiative for cooperation among participants” (I_{34}) is highly connected with G_3 , which revealed the motivation of participants to strengthen cooperation. Actions must be taken to improve the performance of the “relational interface” to meet the expectations of all participants.

The “logistics interface” (I_4) is also rated as “fair”, and its synthetic connection degree reveals a higher connection with G_2 than other scales, indicating a certain degree of stability as well. Combined with the weights of the second-level indicators and the results of the single connection degree, “on-time delivery of component to the site” (I_{41}) attracts more attention from experts than “tracking of components in the transportation process” (I_{42}). However, the actual performance of the “on-time delivery of component to the site” (I_{41}) is poorer than that of “tracking of components in the transportation process” (I_{42}). This sharp contrast should be taken seriously.

5. Discussion

The “fair” performance levels of all the first-level indicators show that the IM of PC is not satisfactory. It is urgent to arouse people’s attention to IM for the PC project.

The IM performance of the “physical interface” is mainly reflected in the operational level. As the main influencing factor of the “physical interface”, standardization is always regarded as the most burning problem to be solved in the promotion of PC. Policies have been formulated to promote the standardization level of PC. However, in this case, standardization-related indicators (“design standardization degree” and “standardization degree of process interface”) show the poorest performance at “poor”. Moreover, the poor performance of “complexity of entity interface” indicates that interface complexity is a key barrier to the IM of PC. Precise component layering and simple interface design

will be of great help to improve IM performance and even to the success of the whole project. It cannot be neglected that the “precision control of component manufacturing” is “good”, indicating that the factory manufacturing of components does improve the quality. However, the overall poor performance reveals that even if the quality of components had been improved through factory production, the PC project has not achieved good performance due to the low degree of standardization and high complexity of the interfaces.

For the “information interface”, the project under assessment has established a unified information platform and provided mobile internet terminal services in the construction. Managers and technicians can directly query project information using mobile devices, leading to a “good” performance for “timeliness of information transfer” and “integrity and accuracy of design information”. Imperfectly, the communication tools such as documents, telephones, and WeChat (similar to WhatsApp in the US, the most popular social app in China) are still important tools for information transmission in the actual construction process, resulting the performance of “standardization of information transmission and storage” staying at the “fair” level, affecting the overall performance of the “information interface”. What is more, the limited “degree of information sharing” due to participants’ protection of core knowledge is also an important factor hindering the performance improvement of the “information interface”.

The “fair” performance of the “relational interface” responds to the research hotspots in the field of cooperative relations in recent years. China has long followed the traditional construction techniques used to decompose the work into independent work packages. Participants are independent of each other and persist in pursuing the maximization of one-sided interests. However, the work tasks at the interface are neglected, and good cooperative relationships cannot be formed between participants. This construction mode divides the integration of the construction process. Despite the continuous learning of the advanced integrated delivery model, engineer procure construct (EPC), design bid (DB), and integrated project delivery (IPD) from developed western countries in recent years, it is hard to develop a stable long-term cooperative relationship among participants because of the long-term inherent sense of separation, resulting in poor performance in the distribution of interests, conflict of goals, and so on. This is confirmed by the poor performance level of indicators such as “clarity of contract responsibility, power and interest” and “conflict of goals” in the case study.

Although there are only two secondary indicators in the logistics interface, the performance is thought-provoking. Viewed from the proportion of weight, “on-time delivery of component to the site” is twice as important as “tracking of components in the transportation process”, but the performance of “on-time delivery of component to the site” is worse than “tracking of components in the transportation process”. To explain this phenomenon, the authors discussed it with experts involved in the research. For PC, component production planning needs to be decided as early as possible to ensure on-site supply. The traditional supply chain has not been completely transformed to adapt to this change. However, the adoption of QR code technology in this project made “tracking of components in the transportation process” achieve a good performance.

6. Conclusions

The IM of the PC projects is a complex, uncertain system, and IM performance is not dependent on a single source but instead on a complex system of disparate factors. In this study, a conceptual IM performance assessment framework was constructed by reviewing existing literature and using the SPA model. The assessment results provided by the framework give managers helpful guidance as they take action to improve the performance of PC projects.

This study advances previous studies as follows. First, given the insufficiency of the literature in evaluating the performance of IM, this study systematically reviewed the relevant literature on IM in PC and identified 19 factors affecting the IM performance. These factors were further grouped into four categories, which provide a better understanding of

the factors affecting IM performance. Second, considering that the previous performance assessment methods cannot adequately consider the uncertainty, the SPA was introduced into this study. The SPA model can fully consider the relationship between IM performance indicators and performance level and determine the membership degree of indicators to performance level. It can not only improve the accuracy of performance assessment but can also predict the development trend of performance. Thirdly, because of the expert scoring method used in this study, subjectivity is inevitable. The OWA operator used in the assessment framework can reduce the impact of extreme values in the expert scoring process to ensure the objectivity of assessment results.

The proposed framework is a useful tool that helps project management teams to improve IM performance in different types of PC projects. It can help managers (1) identify factors that affect IM, (2) measure the influence of influencing factors on the performance of IM, (3) predict the development trend of IM performance, and (4) recognize the main issues for improvement for promoting the IM performance.

The case analysis shows an unsatisfactory IM performance level according to the fair performance of all the first-level indicators, which echoes the late development of PC in China and less application of IM. Other analyses also show that the assessment results can reflect the actual IM issues caused by the policy and project management level, verifying the feasibility and applicability of the assessment framework. Besides, the assessment model can be applied to different PC projects by modifying the indicator system in light of the characteristics of projects, reflecting the possibility of migration and application of the assessment framework.

Although the developed assessment framework can identify the problems of IM in case projects, this project does not represent all projects in China. In the future, more case samples can be used to obtain the general situation of IM practices for PC. Meanwhile, the SPA model application in this paper is not limited to IM performance assessment and can be migrated to more complex and uncertain projects.

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Institutional Review Board Statement: Ethical review and approval were waived for this study, due to this study takes the construction projects as the research object, and the questionnaire survey method adopted in this study is mainly to obtain the opinions of engineers and scholars on the construction engineering issues, which does not involve any ethical issues related to humans or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: Some or all data generated or used during the study are available from the corresponding author by request. (List items).

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