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Developing an Evaluation Model to Measure the Intelligence Level of Smart Industrial Parks

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Abstract: The intelligent development of smart industrial parks (SIPs) can not only promote the development of smart cities, but also promote the development of intelligent large-scale buildings. China is strengthening the construction of SIPs; however, the development of SIPs is limited. Due to different understandings of SIPs, the intelligence level of each SIP varies greatly. It is necessary to develop a SIP intelligence level assessment model to check these limitations. Most of the existing evaluations focus on the qualitative evaluation of the overall intelligence level of SIPs, ignoring the influence of each individual dimension. Therefore, this study used quantitative methods to measure the intelligence level of SIPs from the overall and dimensional levels. The evaluation method included five processes: (1) Classifying the intelligence level of SIPs through expert interviews; (2) Using the literature analysis method to identify various dimensions of the intelligence level; (3) Using literature analysis and expert interviews to determine the evaluation indicators (4) Weighting indicators based on correlation and induced ordered weighted average (IOWA) operator; (5) Using grey clustering analysis to calculate the overall intelligence performance of SIPs and each dimension. Finally, the developed model was verified by Z SIP. The analysis results show that the developed model can measure both overall and dimensional performance of SIPs, and demonstrated that enterprise information services, public information services, SIP security, and energy consumption monitoring platform construction make the greatest contributions to the improvement of the intelligence level. Our research results will help to improve the intelligence level of SIPs, and lay the foundation for the determination of the operating costs of SIPs and the formulation of national standards related to SIPs in the future.

Keywords: smart industrial park; intelligence level; grey clustering analysis; IOWA operator empowerment

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1. Introduction

Smart cities are an important solution to urban problems, and they can improve the accuracy of urban governance, promote environmental protection as well as social management, and contribute to the sustainable development of cities [1–3]. Under the guidance of smart cities, the concept of smart industrial parks (SIPs) has gradually developed [4]. SIPs are the epitome of smart cities, and the practice of smart cities can take SIPs as a traction [5]. The SIPs can not only make use of high technology inside the park to improve the management level and operational efficiency of the park; but also promote the construction of the city through the information interaction between the park and the outside, and the demands of the park [6–8].

As an important part of smart cities, the intelligent development of SIPs drives the development of the industry. While promoting large construction industry development, SIPs open up new application fields for information technology [9]. Integrating new-generation information technology, artificial intelligence, big data, cloud computing, and other emerging intelligent technologies with traditional industrial parks provides a new path for park management. It can provide a new way for park managers to better understand the operation of SIPs, improve their management efficiency, and provide more satisfactory services to enterprises in the SIPs. Therefore, it is meaningful to promote the intelligent construction of SIPs. The strategy of Digital China carries out the top-level design of informatization at the national level. The National Development and Reform Commission and the Ministry of Housing and Urban–Rural Development have issued a series of guidelines related to intelligence, which has promoted the construction of SIPs. As of 2019, more than 60% of the 2543 development zones above the provincial level in China have proposed to build or plan to build SIPs [10].

However, the construction effect of SIPs seems to be limited. There are some problems in the construction of the parks that hinder the improvement of the intelligence level of the parks [11]. For example, the infrastructure of the SIPs is not intelligent enough, the operation and management capabilities are weak, the intelligent services are insufficient, and the parts within the SIPs are still independent of each other [12–15]. These limitations must be examined. In other words, the evaluation of the intelligence performance of the SIP is very important. An effectiveness evaluation method should be proposed to solve the present problems, as without this method it is difficult to effectively guide the construction of SIPs.

Various studies have been conducted on the field of SIP evaluation. Wang developed a combined analytical framework for evaluating SIPs that combines quantitative metrics and subjective judgments with evidence-based inference methods [16]. The Analytic Hierarchy Process (AHP) is the most commonly used method. In combination with the general norms for the construction and management of SIPs, Lu applied the AHP to build an evaluation system for SIPs, providing a theoretical basis for the scientific management and continuous improvement of SIPs [13]. Through case analysis, Dean constructed an evaluation index system including the four dimensions of environment, facilities, business collaboration, and green image [17]. Throughout the existing results, the following deficiencies mainly exist.

(1) The existing index weights are mostly scored by experts, who are easily influenced by expert factors, and so the reliability of evaluation results is not guaranteed. (2) The evaluation of SIPs mainly adopts qualitative evaluation and the AHP, which often focuses on subjective experience and is not objective enough, and ignores the characteristics of the uncertainty of information of certain criteria of the SIPs. (3) Most existing studies focus on the overall performance evaluation, ignoring the evaluation of dimensional performance. In fact, the level of intelligence of SIPs consists of several dimensions. The analysis of the overall intelligence level of SIPs cannot visually reflect the weaknesses of SIPs.

Therefore, the purpose of this paper is to develop a SIP intelligence level assessment model to make efforts to address these deficiencies. This paper made the following attempts: introducing the IOWA operator to attenuate the influence of experts when assigning index weights, using grey clustering analysis to objectively evaluate SIPs, and innovatively proposing a dimensional perspective for SIP intelligence level assessment. Based on this, the specific objectives of this paper are: (1) To determine the intelligence level of the SIPs; (2) To identify the criteria for the intelligence level; (3) To determine the relative importance of these criteria to the intelligence level; (4) To develop an evaluation model that can measure both the overall and dimensional performance of SIPs.

The rest of this study is as follows. Section 2 conducts a literature review. Section 3 develops an evaluation model for SIP intelligence performance. Firstly, the dimensions of the SIP intelligence level are identified through literature survey and expert interviews. Secondly, the index system is selected using literature analysis. In addition, the evaluation is launched using IOWA operator and grey clustering analysis. Section 4 conducts a case study, which demonstrates the application of the model and verifies the reliability of the model, followed by discussions in Section 5 and conclusions in Section 6.

2. Literature Review

2.1. Smart Industrial Parks

SIPs aim to use advanced information technology to realize the intelligent development of parks. The SIPs should integrate internal resources and create a community of interest with information as a link [18,19]. The SIP management platform is considered a solution for the intelligent construction of the SIP [20,21], which can realize information sharing among subsystems and quickly respond to the needs of enterprises in the parks [22–24]. The intelligent construction of SIPs is very necessary [12,25,26]. Wang systematically introduced the solution design of SIP platform, which solves the pain points such as poor service experience and low operational efficiency that traditional parks have been facing for a long time by applying new ICT technologies such as 5G, AI, cloud computing, IoT, and mobile internet [27]. Planning and scheduling vehicles within the campus is also a challenge [28]. Pang proposed that automatic Radio Frequency technology can be used to obtain real-time information to facilitate coordinated fleet planning and scheduling, and designed the advanced fleet planning and scheduling procedures and a reconfigurable service platform [29]. In order to solve the problem of the scientific and reasonable allocation of bandwidth resources in SIPs, Zhou proposed a communication bandwidth prediction technique for smart distribution services in SIPs [30].

Some scholars have discussed the energy issues in SIPs. As an important energy system in SIPs, a distributed energy storage system (DESS) has an important impact on the green and low-carbon development of SIPs. For example, Xi introduced the application of DESSs in the SIPs and analyzed the shortcomings of DESSs in the application at home and abroad [31]. Under the background of promoting the green and low-carbon development of SIPs, solutions such as renewable energy prediction, energy planning, and management can be provided through new technologies such as the IoT [4]. Song analyzed the energy efficiency management of SIPs from a scientific management perspective through data mining, to identify unknown factors that affect the energy consumption, equipment performance, and operational efficiency of enterprises [32]. Hernandez forecasted and optimized energy demand in SIPs [33]. Energy consumption patterns are extremely important for resource optimization and green trends. Hernandez proposed a data processing system that can analyze energy consumption patterns in SIPs, laying the groundwork for improvements in energy consumption patterns [34]. Energy symbiosis is another research direction of energy issues in SIPs. Butturi presented the energy symbiosis solution, highlighting the main ways to achieve energy synergies [35].

In China, many cities have incorporated the construction of SIPs into their urban development plans. SIPs have more advantages than traditional industrial parks. First, in terms of park management and business operation efficiency, SIPs can operate more efficiently using technologies such as big data and the IoT. Second, the digitalization level of SIPs is much higher than that of traditional parks, and they can provide better public services. Thirdly, the SIPs will be greener and more efficient compared with traditional industrial parks.

2.2. Smart Industrial Parks Evaluation

The most common method used to evaluate SIPs is hierarchical analysis (AHP). Wang used the AHP to evaluate the North-South Campus of the State Grid Customer Service Center and analyzed the deficiencies of the campus in terms of ecological environment, management levels, energy utilization, and economic benefits [36]. Guo took Shenzhen Smart Park as an example, constructed an index system that takes into account both commonality and individuality, and launched a comprehensive evaluation using the AHP to determine the level of intelligence of this park [37]. Some other scholars, using Benefit Analysis and DEA, evaluated it. Guo used Benefit Analysis to evaluate SIPs and found that industrial symbiosis can bring significant environmental and economic benefits to parks through knowledge sharing [38]. Yang used Benefit Analysis to compare SIPs with traditional industrial parks and found that SIPs are more sustainable than other industrial parks [39]. Zhao used the best–worst method (BWM) to evaluate the overall benefits of SIPs and ranked the selected SIPs in terms of their overall benefits [40]. Using the DEA method, Liu found that the environmental performance of China's SIPs is improving [41]. A summary of these evaluation methods is presented in Table 1.

Table 1. Smart industrial park intelligence level dimension division.

Research Work	Evaluation Methodology	Analysis
[37]	AHP	The hierarchical analysis method is to break down the research objectives into levels such as guidelines and programs, on the basis of which qualitative and quantitative analyses are conducted, but this method is more subjective.
[38]	Benefit Analysis	Benefit analysis can quantitatively assess the benefits of SIPs, but, due to the pursuit of quantification, the selected index system is not comprehensive enough.
[40]	BWM	Tentative application of BWM to multi-criteria decision problems. However, there is ambiguity and uncertainty because of the qualitative human judgment involved.
[41]	DEA	Although DEA can reduce human-induced errors, it relies on the overall score for evaluation.

However, these evaluation methods are subjective and ignore the fact that the intelligence level of SIPs is influenced by multiple dimensions. In practice, several policies or assessment criteria regarding SIPs contain multiple dimensions. For example, Chongqing Municipality released the Evaluation of Chongqing Smart Industrial park, which divides the SIP into six dimensions: park management, infrastructure, park services, industrial intelligence, guarantee system, and municipal platform interface [42]. The Construction and General Specification of Smart industrial park issued by Shandong Province gives the construction requirements of SIPs in four dimensions: infrastructure layer, support platform layer, intelligent control layer, and intelligent application layer [43]. The evaluation standard of green smart industrial park issued by China Engineering Construction Standardization Association divides the dimensions of SIPs into infrastructure, ecology and livability, management and service, and security and operation and maintenance [44]. Some other standards also interestingly divide SIPs into dimensions for evaluation. In the academic world, scholars usually divide the indicators into several dimensions when establishing the indicator system as well. According to Giffinger, SIPs can be evaluated in six aspects, namely, economy, management, governance, transportation, smart environment, and living [45]. With the increasing environmental problems, many scholars have considered the environment an important dimension in evaluating SIPs. For example, Valenzuela-Venegas extracted evaluation indicators by scouring the relevant literature on Institute for Scientific Information (ISI) and categorized them into three dimensions: social, environmental, and economic sustainability [46]. Dean divided the indicator system into four dimensions, the environment, facilities, industrial synergy, and green image [17]. Wang evaluated SIPs in terms of four elements: planning, near-zero carbon technology, carbon emission management, and environmental health [47]. The core of the construction of smart communities and smart campuses is similar to that of SIPs, they are all about rational integration of internal resources through information and communication technology. Therefore, the evaluation of smart communities and smart campuses has some reference value for SIPs. Tobey assessed smart communities in terms of resilience, economy, sustainability, and society [48]. Wang assessed the sustainability of smart communities in four aspects: security system, infrastructure, community services, and community management [16]. Although these studies have made some contributions to the evaluation of SIPs, there are still some shortcomings, for example, most of the assessments rely on the overall score to measure the intelligence level of SIPs and ignore the intelligence level of individual dimensions. In addition, the evaluation of SIPs is a multi-criteria decision problem, and there is also the problem of unclear information on some of the evaluation indicators, which is often overlooked in existing assessments.

By sorting through the existing literature, we can draw the following conclusions. Firstly, the current research on SIPs focuses on smart construction and energy issues. Although the evaluation of SIPs plays a crucial role in ensuring the effectiveness of its implementation and development, not many articles have been written on the evaluation of SIPs. Secondly, the existing assessment methods are mainly qualitative evaluation or AHP, which lack objectivity, and some other methods cannot deal with unclear information of indicators and cannot solve the evaluation problem of aggregating information of multiple indicators. Finally, the existing evaluation mainly focuses on the SIP as a whole, while the intelligence level of the SIP is affected by each dimension. In other words, the existing evaluations ignore the impact of individual dimensions. Therefore, considering these existing problems, it is necessary to establish a suitable evaluation model, which can measure the overall intelligent performance of SIPs and various dimensions, and provide a new path for evaluating the intelligence level of SIPs.

3. Research Methodology

3.1. Overviews

This study aims to develop an evaluation model to assess overall and dimensional intelligent performance of SIPs. When applying the model, there are five steps, as shown in Figure 1. First, the level of SIP intelligence needs to be classified, and this step can be achieved through expert interviews [49]. Second, the dimensions of SIP intelligence level should be determined. This is normally conducted through literature review [50]. Thirdly, the index system is constructed, which can be screened by literature review and expert interviews to find a reasonable index system [51,52]. Fourth, assigning weights to indicators by using IOWA operator, which can consider the influence of individual experts on the overall results and attenuate this influence by using induced factors [53]. Fifth, grey clustering analysis is used to assess the intelligence level of the SIP. Grey clustering has been widely used in the assessment of various fields because of its ability to deal with the problems of unclear information of indicators and the lack of a requirement for sample size [54–56].

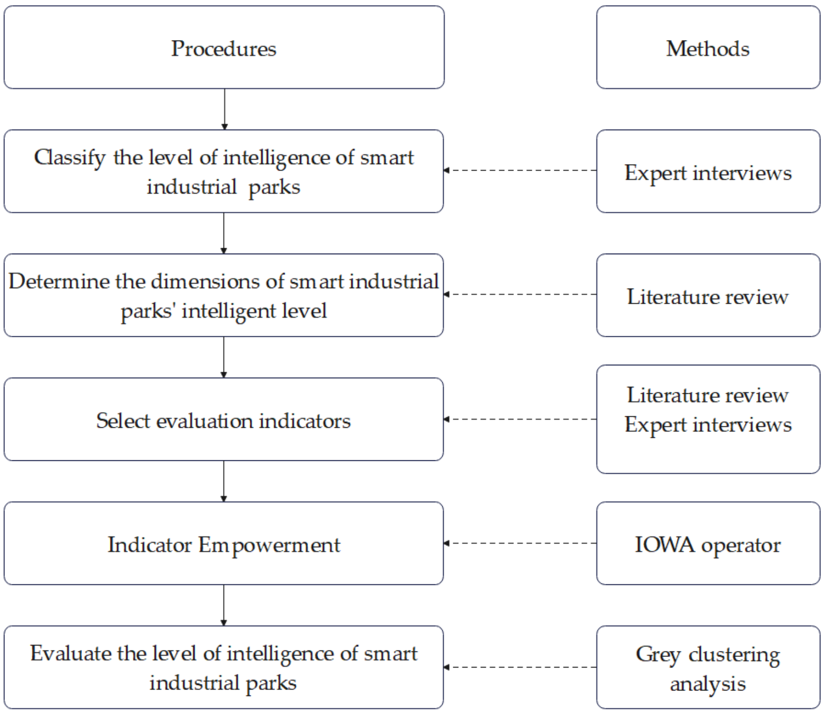

Figure 1. Five procedures for assessing the intelligence level of SIPs.

3.2. Defination of Smart Industrial Parks Intelligence Level

Although China's SIPs started late, they are developing more rapidly and are becoming more skilled in the use of smart technologies. The researchers conducted semi-structured interviews on the topic of SIP intelligence level determination from March to early April 2022 with experts in the field of SIPs. We selected five experts, all of whom have more than four years of experience in SIP research or construction and have participated in several summits on topics related to smart cities and SIPs, being familiar with the situation related to SIPs in China, so they are representative. Table 2 shows the basic information of the five experts. We conducted face-to-face interviews or telephone remote interviews with five experts. Before the semi-structured interviews began, the researchers explained the outline of this interview to the experts and provided them with relevant information about the intelligence level classification of SIPs, such as the Evaluation Criteria of Chongqing Smart Industrial Parks, the White Paper on Future Smart Industrial Parks released by Huawei, and related news and papers, as well as exchanged information in response to the experts' questions to ensure that each expert was familiar with the purpose of this interview. Ultimately, based on the feedback from experts, the current situation of SIPs in China can be divided into four levels: simple level, normative level, mature level and optimization level, respectively defining the degree of intelligence of each level of SIPs. The intelligence level of the park will increase with the improvement of the level. The structure of the intelligence level of SIPs is schematically shown in Figure 2.

Table 2. Composition of experts.

Experts	Position	Years	Additional Information
Expert A	Professor	8	One of the first scholars to conduct research on the SIP framework.
Expert B	Professor	6	Organized several digital construction related subjects for SIPs.
Expert C	Senior Engineer	5	Participated in many SIP construction projects, familiar with the actual situation of the SIPs.
Expert D	Senior Engineer	5	SIP developers who understand the needs of SIPs.
Expert E	Senior Management	6	Has been engaged in the operation and management of SIPs and smart communities.

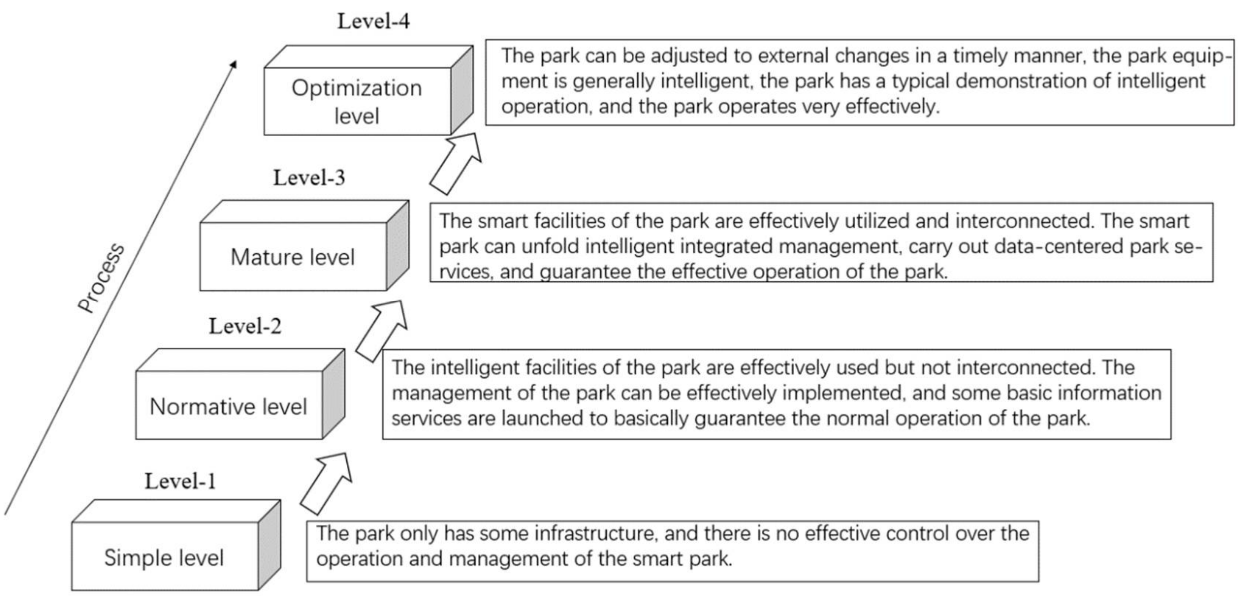

Figure 2. Smart industrial park intelligence level structure diagram.

3.3. Establishment of the Evaluation Indicator System

3.3.1. Smart Industrial Parks Intelligence Level Dimension Division

The overall intelligence level of SIPs is contributed by various dimensions. As introduced in Section 2.2, many existing standards and specifications, as well as scholars' classification of SIP index systems, divided SIPs into multiple dimensions. Based on local standards and related literature, we summarized several commonly used dimensions, as shown in Table 3. We analyzed these dimensions and found that some dimensions have the same meaning, and these dimensions can be combined. For example, park services and the smart application layer can be unified and merged into park services. The focus of this paper is on the intelligence level of the SIPs, and the dimensions that have little significance for the reference of the intelligence level are removed, such as the dimension of "society", which does not contribute significantly to the intelligence level of SIPs, so this dimension is not considered in this paper. Similarly, we can acquire other dimensions of the evaluation index. Finally, we identified four dimensions of SIPs: green and low-carbon C_1, intelligent facilities C_2, park services C_3, and operational efficiency C_4.

Table 3. Smart industrial park intelligence level dimension division.

Dimensions	Definition	Reference							
		[17]	[45]	[46]	[48]	[16]	[42]	[43]	[44]
Environment	SIPs should control the environment in the parks to ensure a green and low-carbon development.	√		√	√				√
Facilities	SIPs should be equipped with a variety of information infrastructure and have multiple intelligent devices.	√				√	√		√
Industry	The construction of SIPs should drive the development of industries in the parks.	√					√		
Management	SIPs manage the environment and information of the parks through several subsystems.		√			√	√	√	√
Security	SIPs should ensure the security of the park and realize security mechanisms such as entrance management and system security response.					√			√
Transportation	SIPs should have an intelligent transportation system to ensure green and convenient travel in the parks.		√						
Living	SIPs should provide a suitable environment to improve the comfort of the people in the parks.		√						√
Economy	The construction of SIPs should drive economic development.		√	√	√				
Social	The construction of SIPs should contribute to society in terms of human, economic, and environmental impact.			√	√				
Services	SIPs should provide various intelligent services using the intelligent systems owned by the parks.					√	√		√
Smart Applications	SIPs integrate the resources of the parks through high technology, thus launching a variety of intelligent applications.						√	√	

3.3.2. Selection of the Evaluation Indicators

The candidate evaluation indicators of SIPs were collected by literature review and the selected indicators were determined by expert review. Since there are some commonalities in the embodiment of intelligence levels in smart communities, smart campuses and SIPs, in order to ensure the comprehensiveness of the indicators, we will also refer to the relevant literature on the assessment of intelligence levels in smart communities and smart campuses. First, the initial index system was obtained by screening the relevant literature by entering words and phrases such as smart industrial park, smart community, smart campus, and evaluation, into the Web of Science and CNKI. Then, we optimized the indicator system by interviewing six experts, and all participants (1) had at least 5 years of research or work experience, (2) were directly or indirectly involved in SIP projects, and (3) were continuously interested in SIP-related developments. Interviewees were asked to provide their reasons for the selection or removal of indicators. After collating the experts' opinions, we deleted some unrepresentative indicators, such as waste heat recovery utilization rate, which is not applicable to all industrial parks, so this indicator was deleted. Considering the practicality of the evaluation model, the number of indicators should not be too many, and some indicators were aggregated into a large category, for example, the establishment of BIM library and GIS library, and such indicators that examine information services were merged into enterprise informatization services. The selected indicators for measuring intelligent performance are shown in Table 4.

Table 4. Evaluation indicators for measuring intelligent performance of SIP.

	Indices	Indices Interpretation and Explanation	Literature Sources of Indices
Green and Low-carbon C_1	Renewable Energy Use C_{11}	The status of the use of renewable energy sources such as solar energy in SIPs.	[46,47,57,58]
	Carbon emissions per unit of energy consumption C_{12}	Examine whether the SIP is a low-carbon development.	[46,47,57]
	Proportion of green buildings C_{13}	The percentage of green buildings included in the SIP. Green buildings are evaluated according to the national standard Green Building Evaluation Standard.	[36,46,58]
	Proportion of green trips C_{14}	SIPs should provide more green travel tools to reduce environmental pollution.	[46,47]
	Pollutant-free treatment C_{15}	The level of harmless treatment of waste, sewage, and other pollutants in SIPs.	[36,46,47,57]
	Water Reuse Rate C_{16}	Reuse of water as a percentage of water consumption.	[46,47]
	Green space ratio C_{17}	Increasing the green space ratio can improve the air quality of the park.	[46,47]
	Energy consumption monitoring platform construction C_{18}	The testing platform can monitor and supervise the energy consumption in real time so as to achieve the energy saving target.	[16,42,47,57–59]
Intelligent Facilities C_2	Fixed Communication Network C_{21}	Meet the immediate and long-term communication needs of the campus.	[16,36,42,58]
	Wireless LAN C_{22}	It should be designed for the users' needs and with the requirement to improve the quality of campus services.	[16,36,42,58]
	Mobile Communication Network C_{23}	Ensure full coverage of communication signals.	[16,36,42,58]
	Park One Card C_{24}	One IC card should meet a variety of functions to make life in the park more convenient.	[16,36,57]
	Intelligent Lighting System C_{25}	Intelligent control of lighting systems using technologies such as the Internet of Things.	[36,42,57]
	Smart industrial park Security C_{26}	Ensure the security of the parks through intelligent analysis.	[16,42,57,58,60]
	Intelligent Fire Fighting C_{27}	Integrating GIS and other technologies to protect people's lives and property.	[42]
	Intelligent Traffic Management C_{28}	Solving traffic problems in the park using technologies such as the Internet of Things.	[42,47,57,60]
park services C_3	Enterprise Information Service C_{31}	Create various databases to facilitate information mining for companies.	[42,57–59]
	E-Commerce Services C_{32}	Services provided for e-commerce applications to facilitate business operations.	[57,58,60]
	E-logistics Services C_{33}	Use of electronic means to achieve logistics informatization.	[57–60]
	Public Information Services C_{34}	Provide public information services such as industry dynamic information and related policies to enterprises.	[16,42,46,57,60]
	Merchandising Services C_{35}	Provide investment services such as occupancy application and policy consultation to enterprises.	[42,57,58]
	E-Government Services C_{36}	The SIP should be docked to the online government function.	[16,42,57,60]
	Business Incubation Services C_{37}	The SIP should achieve precise incubation.	[42,57,58]

Table 4. *Cont.*

Indices		Indices Interpretation and Explanation	Literature Sources of Indices
Operational Benefits C_4	Total output value of the park C_{41}	The total output value of the SIP refers to the total industrial output value of the park.	[36,46]
	Park net labor income C_{42}	The net income of the park examines the level of profitability of the park's projects.	[36,46]
	Industry Aggregation C_{43}	Evaluate the work of the park in promoting industrial agglomeration.	[46]
	New jobs C_{44}	Examining the benefits the park brings to society.	[36,46]

3.4. Determination of Index Weights Based on Correlation and Induced Ordered Weighted Operator

The traditional assignment methods include the AHP, entropy method, and expert scoring method; these methods rely on experts' knowledge of the evaluation object to a large extent. However, due to the different experiences and ideas of each expert, different experts have different opinions on the importance of the same indicators. The correlation degree and induced ordered weighted average (IOWA) operator can effectively solve the impact of this problem. In this paper, the correlation is used to measure the data with different "differences", so as to control the influence of the assignment of different experts on the overall weight, and the IOWA operator is used to integrate the weight information of multiple indicators when the expert's own weight is unknown [61].

3.4.1. Correlation-Based Measure of Variability of Weighted Information

In the process of weight determination, individual experts' perceptions of the importance of the same indicator are consistent within a certain range. However, due to the differences in experts' work experience and personal preferences, there are "individual variability" in individual experts' perceptions of the importance of the same index. This "individual variability" can be divided into two categories. In the overall trend distribution of indicator weights, smaller "individual variability" is called "weak variability", and conversely, "strong variability" When the weight information is assembled, the weight information with less "individual variability " is the main one.

Correlation reflects the degree of correlation between different things. In this paper, correlation is used to measure the consistency of an individual expert's judgment on the weight of an index relative to the judgment of the expert group. The steps to calculate the effect of individual weights on the overall weight using the correlation are as follows.

Step 1. Assume the number of experts is p, the set of experts is $B_t(t = 1, 2, \cdots, p)$, and the score data set of expert t on indicator i is $R_{it} = \{r_{i1}, r_{i2}, \cdots, r_{ip}\}$.

Step 2. Solve for the overall distribution function of the weighted data set.

Based on the characteristics of the subjective preference of the expert group for indicators and the universality of the normal distribution, We consider $\{r_{i1}, r_{i2}, \cdots, r_{ip}\}$ as a set of sample values from the overall set of weighted data for indicator i [62,63]. The maximum likelihood estimate of the weight dataset $\{r_{i1}, r_{i2}, \cdots, r_{ip}\}$ for indicator i is used as the eigenvalue of the overall distribution of the weights, and the maximum likelihood estimates of u and σ^2 are calculated by the following formula.

$$\begin{cases} \hat{\mu} = \frac{1}{n}\sum\limits_{t=1}^{p} r_{it} \\ \sigma^2 = \frac{1}{n-1}\sum\limits_{t=1}^{p}\left(r_{it} - \frac{1}{n}\sum\limits_{t=1}^{p} r_{it}\right)^2 \end{cases} \tag{1}$$

Step 3. Weighted scoring partition.

The probability interval of the sample distribution is shown in Figure 3. The scoring values between $[\mu - \sigma, \mu + \sigma]$ have "weak variability" and outside have "strong variability".

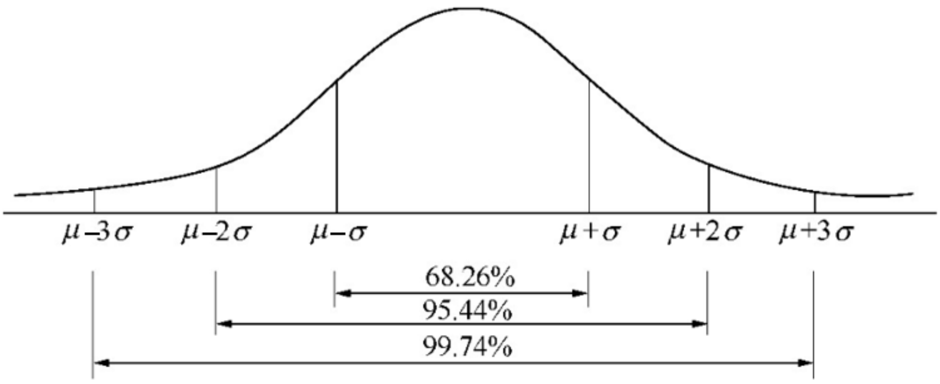

Figure 3. Sample distribution probability.

Step 4. Calculate the correlation ε_{it} of the weight scores r_{it} given by individual experts with respect to the overall distribution of the weights of indicator i.

(1) Calculate the absolute distance Δ_{it} of a single expert's score r_{it} for indicator i relative to the mean value μ of the overall distribution of indicator i:

$$\Delta_{it} = |r_{it} - \mu|, t = 1, 2, \cdots, p \tag{2}$$

(2) Standardized processing:

$$\varepsilon_{it} = \frac{\Delta_{it}(min) + \rho\Delta_{it}(max)}{\Delta_{it} + \rho\Delta_{it}(max)}, t = 1, 2, \cdots, p \tag{3}$$

where $\Delta_{it}(min)$ and $\Delta_{it}(max)$ are the minimum and maximum values of the set $\{\Delta_{i1}, \Delta_{i2}, \cdots, \Delta_{ip}\}$, respectively; ρ is the resolution coefficient. In grey correlation analysis, generally the value of ρ is taken as [0.1, 0.5] [64]. ρ = 0.1 for $\Delta_{it} \notin [\mu - \sigma, \mu + \sigma]$; ρ = 0.5 for $\Delta_{it} \in [\mu - \sigma, \mu + \sigma]$ [63].

3.4.2. Determination of Weights Based on the IOWA Operator

The OWA operator and the IOWA operator are defined as follows.

Definition 1. *An OWA operator of dimension n is a mapping OWA: $R^n \to R$ that has an associated weighting vector $W = (w_1, w_2, \cdots, w_n)^T$ of dimension n with $w_j \in [0,1]$ and $\sum_{j=1}^{n} w_j = 1$, then the algorithms of OWA operator is:*

$$OWA(a_1, a_2, \cdots, a_n) = \sum_{j=1}^{n} w_j b_j \tag{4}$$

where b_j is the element in the jth position after the elements in $(a_1, a_2, \cdots, a_n)$ are sorted from large to small.

Definition 2. *An IOWA operator of dimension n is an application IOWA: $R^n \times R^n \to R$ with an associated weighting vector W of dimension n, where the sum of the weights is 1 and $w_j \in [0,1]$ and where an induced set of ordering variables (v_i) is included, then the algorithms of the IOWA operator is:*

$$IOWA(\langle v_1, a_1 \rangle, \langle v_2, a_2 \rangle, \cdots, \langle v_n, a_n \rangle) = \sum_{j=1}^{n} w_j b_j \tag{5}$$

where v_i is the order-inducing variable, and a_i is the argument variable. b_j is the a_i value of the OWA pair$\langle v_i, a_i \rangle$ at the jth position after the induced factor (v_i) is sorted in descending order.

The correlation calculated in Section 3.4.1 will be used as an induced factor to rank the assignments of each expert. The specific calculation steps are as follows.

Step 1. According to OWA operator theory, $(a_1, a_2, \cdots, a_n)$ is arranged in descending order and numbered from 0. The result is $b_0 \geq b_1 \geq \cdots \geq b_{n-1}$. The weight w_j of data b_j is calculated using the combination number C_{n-1}^{j}, and $\sum_{j=0}^{n-1} w_{j+1} = 1$.

$$w_{j+1} = \frac{C_{n-1}^{j}}{\sum_{k=0}^{n-1} C_{n-1}^{k}} = \frac{C_{n-1}^{j}}{2^{n-1}} \tag{6}$$

Step 2. When using the IOWA operator to calculate the weights, an expert's score for an indicator is used as a_j, and the correlation obtained according to Equation (3) is used as the induced value, then p two-dimensional arrays $(\langle \varepsilon_1, a_1 \rangle, \langle \varepsilon_2, a_2 \rangle, \cdots, \langle \varepsilon_n, a_n \rangle)$ are obtained, and the absolute weights $\overline{w}_i$ of the indicators are obtained using the set of Equation (5).

Step 3. The information of each index weight is normalized to obtain the final weight of the index

$$w_i = \frac{\overline{w}_i}{\sum_{i=1}^{m} \overline{w}_i} \tag{7}$$

where m is the number of indicators contained in the dimension to which indicator i belongs.

3.5. Calculation of Performance Score Based on Grey Clustering Analysis

Most studies on the evaluation of SIPs have been analyzed using the Analytic Hierarchy Process (AHP) [36]. Although the AHP can solve multi-criteria decision-making problems, it is highly subjective, making it difficult to ensure the validity of the results [65]. In terms of evaluation methods, AHP [66], FCE [67], PCA [68], and structural equation are all commonly used evaluation methods. However, the results obtained by the AHP and FCE are often subjective and affect the scientific nature of the final evaluation results, while PCA requires a large amount of sample data, and it is difficult to obtain numerous samples for this experiment, so they are not suitable for this study. The comprehensive evaluation of the intelligence level of SIPs is a complex system with multiple indicators, levels, and attributes. Its difficulty lies in the fact that there are many indicators, and some information of the indicators has incomplete and unclear characteristics. Grey system theory is devoted to studying small samples and information-poor problems and provides a new method to solve these problems. Therefore, grey clustering analysis is chosen in this study to assess the intelligence level of SIPs.

The grey system theory was put forward by Chinese scholar Professor Deng Julong, and it is widely used in various fields of engineering and management [69–71]. Grey clustering analysis is a classic evaluation method of grey system theory. By establishing the central-point triangular whitenization weight function (CPTWWF), the whitenization value of the corresponding grey number of each grey class is calculated, so as to complete the conversion of the evaluation system from the grey system to the white system. Combined with the relative weights of the indicators determined by IOWA operator, a comprehensive evaluation model of the intelligence level of SIPs is established through the following four steps.

Step 1. Divide into grey classes.

According to the grade classification of SIP intelligence level and combined with experts' opinions, the evaluation objects are divided into four grey classes, and the specific quantification adopts the ten-point system, as shown in Table 5.

Table 5. Grey class classification level and score range.

Optimization Level	Mature Level	Normative Level	Simple Level
[9,10)	[6,9)	[3,6)	[0,3)

Step 2. Construct the improved CPTWWF.

Suppose there are *s* grey classes, let λ_k be the centroid of the grey class k, and connect the point (λ_k, 1) of the grey class k with the central-point (λ_{k-1}, 0) of the grey class $k-1$ and the central-point (λ_{k+1}, 0) of the grey class $k+1$ at the same time, we can determine the triangular whitenization weight function (WWF) $f_j^k(x)(j = 1, 2, \cdots, n)$ of the indicator j with respect to grey class k. However, when the value range of indicator j is extended outward, the extended result may cause errors in clustering. Therefore, the CPTWFF is improved by replacing the moderate measure the WWF, which is at the beginning and end of the original function, with the lower limit measuring WWF and the upper limit measuring WWF, respectively [72], and the function image is shown in Figure 4. In other words, when $k = 1$, the lower limit measure WWF is used, extending to 0 to the left, and when $k = 4$, the upper limit measure WWF is used, extending to 10 to the right. The functional expressions are given in Equations (8)–(10).

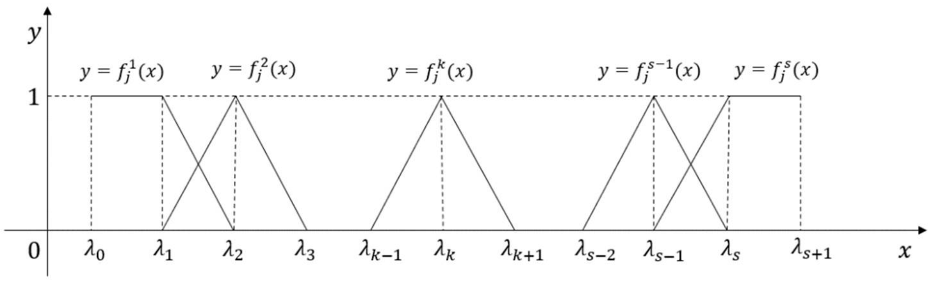

Figure 4. Modified central-point triangular whitenization weight function.

The function expressions are given in Equations (8)–(10).

$$f_j^1(x) = \begin{cases} 0, & x \notin [0, 4.5] \\ 1, & x \in [0, 1.5] \\ \frac{4.5-x}{4.5-1.5}, & x \in [1.5, 4.5] \end{cases} \tag{8}$$

$$f_j^k(x) = \begin{cases} 0, & x \notin [\lambda_{k-1}, \lambda_{k+1}] \\ \frac{x-\lambda_{k-1}}{\lambda_k-\lambda_{k-1}}, & x \in [\lambda_{k-1}, \lambda_k] \quad (k = 2, 3) \\ \frac{\lambda_{k+1}-x}{\lambda_{k+1}-\lambda_k}, & x \in [\lambda_k, \lambda_{k+1}] \end{cases} \tag{9}$$

$$f_j^4(x) = \begin{cases} 0, & x \notin [7.5, 10] \\ \frac{x-7.5}{9.5-7.5}, & x \in [7.5, 9.5] \\ 1, & x \in [9.5, 10] \end{cases} \tag{10}$$

where: $f_j^1(x)$, $f_j^k(x)$, $f_j^4(x)$ are the CPTWWFs of index j with respect to the grey class 1, the grey class k, and the grey class 4, respectively; x is the score of index j; λ_{k-1}, λ_k, λ_{k+1} are the central-points of the ($k-1$), k and ($k+1$) classes, respectively.

Step 3. Calculate the integrated clustering coefficient.

The integrated clustering coefficient σ_i^k of the first-level indicator i with respect to the grey class k is calculated as follows.

$$\sigma_i^k = \sum_{j=1}^{m} f_j^k(x_{ij}) w_i^* \tag{11}$$

where: x_{ij} is the score of the second-level indicator j under the first-level indicator i, and ω_i^* is the weight of the second-level indicator j.

Step 4. Determine the comprehensive evaluation coefficient.

The comprehensive evaluation coefficient ϕ^k is calculated by the following formula.

$$\phi^k = \sum_{i=1}^{n} \sigma_i^k \omega^* \tag{12}$$

where ω^* is the weight of the first level indicator i.

According to $\max_{1 \le k \le s} \left\{ \phi^k \right\} = \phi^{k^*}$, the comprehensive evaluation of the evaluated object can be judged to belong to the grey class k^*.

4. Empirical Analysis Results

4.1. Case Background

Z smart industrial park is located in Beijing, China, and embraces smart characteristics. It was elected as a case-study with which to test the intelligent performance of SIPs. It is a real green-smart industrial park which provides many smart aspects to the management of the park.

The park covers a total area of 719 km^2, of which the first and second phases cover 249 km^2 with a planned construction area of about 2.03 million m^2, mainly for research and development, medical services, incubation, and an industrialization base; the third phase covers an area of about 470 km^2 with a construction area of 3.5 million m^2, and will be built into a new scientific city with the integration of industry and city. In terms of infrastructure, the park provides a broadband network system, one-card, park road traffic system interconnection, etc. It also provides an information technology platform, green low-carbon operation, and other eco-innovation technologies for park occupancy so that the park can operate more efficiently. The park actively uses new-generation information technology such as the Internet of Things, the internet, cloud computing, etc. to promote the intelligence and ecological development of the park, for example, building the park security to ensure the safety of the park, and establishing the environmental testing platform to reduce carbon emissions. In terms of park services, the information platform is built to facilitate the efficient operation of park enterprises. The goal of the park is to build a green and low-carbon SIP that integrates a complete industrial chain with perfect intelligent services. Based on the proposed assessment model, the intelligence level of the park is assessed.

4.2. Weights of Indexes

Five experts in the industry, including but not limited to design institute researchers, SIP operation managers, and SIP construction personnel, were invited to score according to the importance of the indexes using the 0~10 scoring method. We required scores to be given in multiples of 0.5. Based on the data scored by experts and the weighting of IOWA operator, this study calculated the weight of each indicator, as shown in Table 6.

Table 6. SIP intelligence level evaluation index weights.

Dimension	Weight of Dimension	Index	Weight of an Index in Dimension	Comprehensive Weight of an Index
C_1	0.2965	C_{11}	0.1234	0.0366
		C_{12}	0.1436	0.0426
		C_{13}	0.1204	0.0357
		C_{14}	0.1118	0.0331
		C_{15}	0.1286	0.0381
		C_{16}	0.1067	0.0316
		C_{17}	0.1038	0.0308
		C_{18}	0.1617	0.0480

Table 6. *Cont.*

Dimension	Weight of Dimension	Index	Weight of an Index in Dimension	Comprehensive Weight of an Index
C_2	0.2839	C_{21}	0.1238	0.0367
		C_{22}	0.1295	0.0384
		C_{23}	0.1238	0.0367
		C_{24}	0.1148	0.0340
		C_{25}	0.1125	0.0334
		C_{26}	0.1560	0.0463
		C_{27}	0.1125	0.0334
		C_{28}	0.1272	0.0377
C_3	0.3214	C_{31}	0.1821	0.0585
		C_{32}	0.1235	0.0397
		C_{33}	0.1389	0.0446
		C_{34}	0.1774	0.0570
		C_{35}	0.1264	0.0406
		C_{36}	0.1299	0.0418
		C_{37}	0.1218	0.0391
C_4	0.0982	C_{41}	0.2458	0.0241
		C_{42}	0.2514	0.0247
		C_{43}	0.2891	0.0284
		C_{44}	0.2849	0.0280

As can be seen from the result, for the four dimensions of the intelligence level of the SIP, park services C_3 has the highest weight; for all the indicators, enterprise information services C_{31}, public information services C_{34}, and smart industrial park security C_{26} are the indexes with the highest comprehensive weights.

4.3. Grey Clustering Analysis Results

Experts were invited to investigate the situation of the Z smart industrial park and score it according to the evaluation indices. Based on the data scored by experts and grey cluster analysis, this study calculated the overall intelligence performance of Z smart industrial park and its dimensions. The results of the grey cluster analysis are shown in Table 7.

According to the maximum principle of grey class division, it can be concluded that the intelligence level of this overall SIP and its four dimensions are at the mature level.

Table 7. Center point triangular whitening weight function values for each indicator.

Indices	Indices	Score x_{ij}	f_j^1	f_j^2	f_j^3	f_j^4	Integrated Clustering Coefficient σ_i^k			
							Grey Class 1	Grey Class 2	Grey Class 3	Grey Class 4
C_1	C_{11}	6.6	0.0000	0.3000	0.7000	0.0000	0.0000	0.2102	0.7897	0.0000
	C_{12}	6.6	0.0000	0.3000	0.7000	0.0000				
	C_{13}	7.5	0.0000	0.0000	1.0000	0.0000				
	C_{14}	7.2	0.0000	0.1000	0.9000	0.0000				
	C_{15}	7.1	0.0000	0.1333	0.8667	0.0000				
	C_{16}	6.0	0.0000	0.5000	0.5000	0.0000				
	C_{17}	6.1	0.0000	0.4667	0.5333	0.0000				
	C_{18}	7.5	0.0000	0.0000	1.0000	0.0000				
	C_{21}	6.1	0.0000	0.4667	0.5333	0.0000				
	C_{22}	6.4	0.0000	0.3667	0.6333	0.0000				
	C_{23}	6.6	0.0000	0.3000	0.7000	0.0000				

Table 7. *Cont.*

Indices	Indices	Score x_{ij}	f_j^1	f_j^2	f_j^3	f_j^4	Integrated Clustering Coefficient α_i^k Grey Class 1	Grey Class 2	Grey Class 3	Grey Class 4
C_2	C_{24}	7.2	0.0000	0.1000	0.9000	0.0000	0.0000	0.2708	0.6981	0.0312
	C_{25}	6.9	0.0000	0.2000	0.8000	0.0000				
	C_{26}	7.9	0.0000	0.0000	0.8000	0.2000				
	C_{27}	6.0	0.0000	0.5000	0.5000	0.0000				
	C_{28}	6.6	0.0000	0.3000	0.7000	0.0000				
C_3	C_{31}	7.5	0.0000	0.0000	1.0000	0.0000	0.0000	0.1621	0.7847	0.0532
	C_{32}	6.1	0.0000	0.4667	0.5333	0.0000				
	C_{33}	6.9	0.0000	0.2000	0.8000	0.0000				
	C_{34}	8.1	0.0000	0.0000	0.7000	0.3000				
	C_{35}	7.1	0.0000	0.1333	0.8667	0.0000				
	C_{36}	6.4	0.0000	0.3667	0.6333	0.0000				
	C_{37}	7.2	0.0000	0.1000	0.9000	0.0000				
C_4	C_{41}	7.9	0.0000	0.0000	0.8000	0.2000	0.0000	0.0285	0.9810	0.0617
	C_{42}	7.6	0.0000	0.0000	0.9500	0.0500				
	C_{43}	7.5	0.0000	0.0000	1.0000	0.0000				
	C_{44}	7.2	0.0000	0.1000	0.9000	0.0000				
Comprehensive evaluation value φ^k							0.0000	0.1941	0.7739	0.0320

5. Discussion

5.1. Main Findings of the Case Study

As shown in Table 7, the overall intelligent performance of Z SIP is at the mature level, and the four dimensions of green and low-carbon, intelligent facilities, park services, and operational benefits are all at the mature level, indicating that the development of this SIP is more balanced. Z SIP is at a mature level in terms of the green and low-carbon dimension, probably because the shift to a low-carbon development model in Beijing requires efforts from all sectors under the national policy requirement of regional green development [73]. The energy structure upgrade and energy efficiency improvement make the green and low-carbon development of the park possible [74]. The information architecture is the foundation of the services provided by the SIP [75]. The park has achieved full network coverage and various networks are integrated with each other, which allows for the possibility of providing various digital convenience services in the park.

SIPs improve their levels of intelligence through multiple dimensions. The results in Table 6 show the importance of each dimension to the overall intelligent performance of the SIPs. Figure 5 provides a summary version of Table 6 to describe the contribution of each dimension to the intelligence level of SIPs and the composition of sub-criteria under each dimension is shown in Figure 6. As shown in Figure 5, the park service is the most important to the intelligence level of SIPs, and it is an important symbol of the intelligence of SIPs. Using various information technologies to collect and analyze the information data in the parks, SIPs provide various information services for the users of the parks, allow them to experience the convenience and speed brought by technology, and meet the needs of different customers. At the same time, through intelligent services, SIPs guide enterprises in the park to use high technology, and promote the development of the industry [60,76]. Yoon pointed out that it is necessary to actively use information technology to cover the entire manufacturing system, and to use the IoT, big data, cloud computing, and other technologies to empower the manufacturing system, which has become a research hotspot [77]. For the other three dimensions, intelligent facilities improve the management efficiency of the park, the green and low-carbon dimension refers to society's expectation of low-carbon energy conservation in the SIPs under the situation of increasingly serious environmental problems, and the operational benefits dimension is a measurement of the operation effect of SIPs [78].

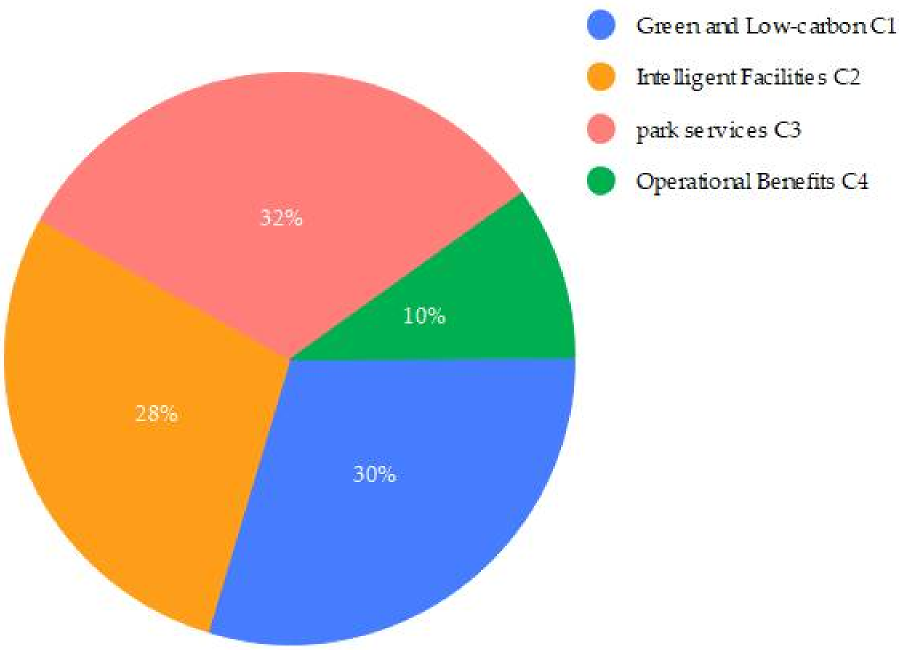

Figure 5. The four dimensions of the intelligence level of the SIPs.

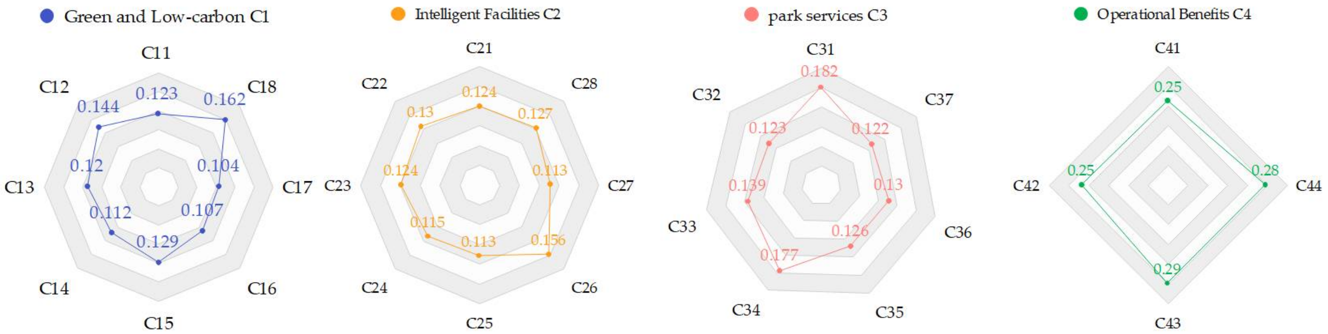

Figure 6. Composition of each dimension of the intelligence level of SIPs.

The weight of enterprise information services C_{31}, public information services C_{34}, and smart industrial park security C_{26} is relatively high, which has a greater impact on the intelligent performance of SIPs. Wang made a similar point, arguing that ICT-based SIP management is the core part of the parks, while the security of the parks is the primary issue that the parks need to focus on [4]. Qi pointed out that the realization of SIPs requires the establishment of an efficient information system, and various public information services as well as information services for all parties in the park [79]. Park security is one of the goals of SIP construction [80]. In addition, it is worth noting that in Figure 6, the energy consumption monitoring platform construction C_{18} is very important for the green and low-carbon dimension of SIPs. The energy consumption monitoring platform can be achieved by relying on IoT technology, which provides an effective monitoring and management solution [81]. To improve the intelligence level of SIPs, we can start from these key indicators. Managers can choose a more robust information platform builder, and each participant can have access to the information they need. Park security is also an important part of the park, and more investment in park security is needed. The parks should also respond to the national call for green development by using a testing platform to strictly monitor carbon emissions, and improve their intelligence levels.

5.2. The Effectiveness of the Proposed Method

It is necessary to effectively evaluate the SIP from both overall and dimensional perspectives. As shown in the case demonstration, the overall performance is at a mature level, and the dimensions C_1 (green and low-carbon), C_2 (intelligent facilities), C_3 (park services), and C_4 (operational benefits) contribute greatly to the improvement of the intelligent performance of SIPs. Therefore, the SIP intelligence level assessment model based on IOWA operator–grey clustering can assess both the overall and dimensional intelligent performance of SIPs. The assessment model contains five procedures, including the classification of the level of intelligence of SIPs, the determination of the dimensions of SIPs' intelligence levels, the construction of the index system, the indicator empowerment, and the evaluation of the level of intelligence of SIPs. Among them, the determination of the intelligence level of SIPs is the key aspect of the assessment.

Through the previous case, it can be proved that the evaluation model proposed in this paper is effective. The performance of this park is at the mature level in four dimensions: green and low-carbon, intelligent facilities, park services, and operational benefits, which is in line with the policy requirements of Beijing and the regional facility conditions in Beijing. This park has been repeatedly used as a typical case of a SIP for other parks to learn from because of its more mature intelligent applications. The relevant discussions show that the method of SIP intelligence level assessment based on IOWA operator–grey clustering proposed in this paper is feasible.

6. Conclusions

As an important part of the smart city, the intelligent development of SIPs can not only promote the development of smart cities, but also promote the intelligent progress of large-scale buildings, so it is necessary to study the level of intelligence of SIPs. The intelligent performance of SIPs is affected by several dimensions, so this paper constructs an evaluation model that can evaluate the overall and dimensional intelligent performance of SIPs.

From this, we draw the following conclusions. First, the intelligent performance of SIPs is the result of the synergy of multiple factors, and the evaluation of SIPs needs to consider both the dimensions and the overall level. Second, our proposed IOWA operator–grey clustering assessment model can evaluate the intelligence level of SIPs from both dimensional and overall aspects. Finally, the validity of the assessment model is verified through case studies, and the key factors affecting the intelligence level of SIPs, enterprise information services, public information services, park security, and energy consumption monitoring platform construction were obtained, and SIP managers can start from these four aspects to improve the intelligence level.

This study enriches the research related to SIPs by introducing a new method, IOWA operator and grey clustering analysis, to evaluate the intelligence level. In addition, the proposed new method provides a new perspective for the evaluation of the intelligence level of SIPs, which considers not only the intelligence level of SIPs as a whole, but also the intelligence level of individual dimensions of SIPs, which is innovative. In real life, the park can use the assessment results of this model to identify the weak links and take corresponding measures to improve the intelligence level. In addition, the research conducted in this paper can provide a reference for the future development of smart industrial parks specifications in China, and the classification of SIPs' intelligence levels can also be used as a basis for determining the operating costs of the parks.

However, there are still limitations to the model. When calculating the index weights using the IOWA operator, the reasonableness of the normal distribution assumption was not further demonstrated, which is a limitation of this paper, so we will continue our study to solve this problem in the future research. In addition, the intelligence level of SIPs is affected throughout the construction life cycle. This research only considered the completed operation period of SIPs when establishing indicator systems. In future research, we hope to improve the evaluation index system. At the same time, it can also be compared with other methods, such as cloud models, etc., and other cases can be conducted to further validate this intelligence level evaluation model.

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