# A Smart Construction Benefit Evaluation Method Combining C-OWA Operator and Grey Clustering

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***Abstract*—Currently, there is a lack of effective objective quantitative methods for evaluating the benefits of smart construction. Therefore, this study proposes a comprehensive method for evaluating the benefits of smart construction. This method establishes an indicator system from the perspective of evaluation objectives, and on this basis, uses a continuous ordered weighted average operator to ensure the objectivity of indicator weight allocation. Afterwards, the grey clustering method is used to form a scoring matrix, achieving effective comprehensive quantitative evaluation. The results showed that for the selected project, the comprehensive benefit value evaluated was 8.342, indicating that the smart construction efficiency of the project had reached a good level. Meanwhile, the extensive benefits of the project showed a stepwise upward trend from 2021 to 2023. This study aims to design and apply a smart construction benefit evaluation method that integrates continuous ordered weighted average operator and grey clustering, which is practical and can provide data reference for project management of smart buildings.**

***Keywords—C-OWA; Grey system; clustering; intelligent construction; sustainability***

## I. INTRODUCTION

With the development of modern technology, smart construction is gradually changing traditional construction and operation modes. However, there are currently difficulties in evaluating the Benefits of Smart Construction (SCB) projects, mainly due to the uncertainty and complexity of the evaluation information. In order to effectively evaluate the comprehensive SCB projects, it is necessary to develop customized evaluation methods that are more suitable for smart buildings [1-3]. When evaluating the SCB, there is often a situation where multiple standards compete with each other and evaluation information is contradictory. In addition, the information in the evaluation process is often accompanied by uncertainty. Therefore, in order to conduct effective and comprehensive evaluation, it is necessary to have an evaluation method that can effectively reflect multiple criteria and handle uncertain information. The Complex Ordered Weighted Average (C-OWA) operator is an effective tool for this field, which can integrate multiple evaluation criteria based on the importance of information and the risk attitude of decision-makers [4-6]. Grey system theory is also an effective tool, which is used for the effective and accurate classification of imprecise data. By combining the C-OWA operator and grey clustering method, it is possible to objectively evaluate the SCB projects containing uncertain information while considering the preferences of decision-makers [7-8]. Therefore, this study proposes a Smart Building Benefit Evaluation (SBBE) framework that integrates the C-OWA operator and grey clustering, and verifies the practicality and effectiveness of the framework through case analysis. Section II of this study proposes the research objectives. Section III proposes an SBBE method that integrates the C-OWA operator and grey clustering, and establishes an indicator system. Section IV calculates indicator weights, while Section IV and Section V gives details about results and conclusion respectively.

Although smart buildings have brought advantages such as cost reduction, efficiency improvement, and project sustainability improvement to the traditional construction industry so far, the current application of smart building technology is still not widespread and in-depth enough, resulting in a lack of standardized comprehensive benefit evaluation methods. In the evaluation of the benefits of smart buildings, firstly, there are differences in the evaluation standards among various parties, making it difficult to unify and compare them; Secondly, current evaluation methods may encounter issues such as inaccurate results when evaluating project information with high uncertainty; Thirdly, the current evaluation methods have not taken into account the technological advancement of smart buildings.

In order to solve the problems of current smart building benefit evaluation methods, a smart building benefit evaluation method combining C-OWA operator and grey clustering technology is proposed. The C-OWA operator can adjust weights based on the importance of information and the attention of decision-makers, while grey clustering technology can effectively classify imprecise information in the evaluation process, thereby achieving quantitative evaluation of uncertain information. By combining two methods, it can be ensured that the evaluation method has unified quantitative standards, can quantitatively evaluate uncertain information, and ensure consideration of technological progress.

Although the evaluation methods for research design are systematic and applicable. However, it still has certain limitations. The design of this study is a standardized system, so in actual project information evaluation, the system is likely to face extreme information caused by external factors. When dealing with similar extreme information, the system may experience certain inaccuracies. Therefore, special system modifications for extreme situations are the future research direction.

## II. Related Works

In terms of the digital application of C-OWA and grey system, Liu H's team designed an evaluation system for the Quality of College English Teaching (CETQ), and combined grey clustering analysis and entropy weight method to construct a comprehensive evaluation model. It provided an effective solution for objectively evaluating CETQ [9]. Zhang D's team proposed a recognition technology based on a multi-sensor data collection cloud platform and an improved particle neural network method. This technology achieved real-time monitoring of the pouring interface by monitoring the parameters of the concrete pouring surface [10]. Du X et al. constructed a group decision information fusion model that takes into account the incompleteness and uncertainty of decision information. The team proposed an interval intuitionistic fuzzy combination weighted average operator to solve the data position weight limitation problem of existing operators when summarizing data. This method effectively improved the accuracy of group consensus [11]. Peng B's team believed that there were two problems in Pythagorean Fuzzy Multi-attribute Group Decision-making (PFMAGD): the convergence operator problem of extreme fuzzy evaluation, and the risk attitude problem of decision-makers. Therefore, to address these issues, this study redesigned the evidence reasoning aggregation method in intuitive fuzzy environments and proposed a risk attitude-based PFMAGD method. The new method overcame the shortcomings of existing methods in the Pythagorean fuzzy environment [12].

In terms of building efficiency evaluation, Le Thi H TKO et al. focused on the concept of green buildings and global development trends, and analyzed the significant benefits brought by green buildings based on practical cases in Vietnam. The research results provided sufficient reference basis for decision-making in green building projects [13]. Yu L et al. explored the application methods of deep reinforcement learning in energy management of intelligent buildings. The energy consumption and carbon emissions generated by traditional buildings accounted for about 30% of the total energy consumption and carbon emissions. Therefore, improving energy efficiency to promote the development of green buildings was imperative [14]. Scholars such as Alshammari K analyzed the application of the Internet of Things (IoT) in building environments and looked forward to the role of digital twin technology in improving the security level of smart cities. This study suggested expanding the scope of Building Information Modeling (BIM) standards to adapt to the development of IoT, while enhancing network security standards to ensure that future smart city construction can align with digital twin technology [15]. Kumar A et al. proposed a building architecture that combines constrained application protocols and data packet transport layer security protocols to optimize energy management, reduce building energy consumption, and improve the efficiency and security of the entire system. The simulation results showed that this method could reduce the energy consumption of smart buildings by about 30.86% [16].

In summary, in recent years, research in multiple fields such as intelligent building monitoring, group decision-making information fusion, and SBBE has been deepened. Meanwhile, these studies also indicate that the promotion of green buildings, the intelligence of energy management, and the application of IoT technology have become important topics in the construction industry. Compared to these, the innovation of this study lies in the comprehensive use of the fusion technology of C-OWA operator and grey clustering to improve the effectiveness of decision-making and evaluation models, and enhance the reliability and practicality in SBBE.

## III. SBBE Method Combining C-OWA Operator and Grey Clustering

This study first constructs an indicator system. To ensure the scientificity and practicality of the evaluation system, researchers provide an objective and detailed weight allocation plan through expert consultation and empirical verification and then use the C-OWA weighting method. Finally, the grey clustering method is used to transform incomplete or fuzzy information into grey evaluation coefficients using Whitening Weight Functions (WWF), thereby forming a clustering score matrix.

### A. Construction of SBBE Indicator System

To construct a scientific and systematic SBBE indicator system, this study integrates the principles of system comprehensiveness, scientific rationality, practicality and operability, goal orientation, inheritance and innovation, and establishes an indicator system that integrates smart construction technology with sustainable new development goals. The technical roadmap is Fig. 1.

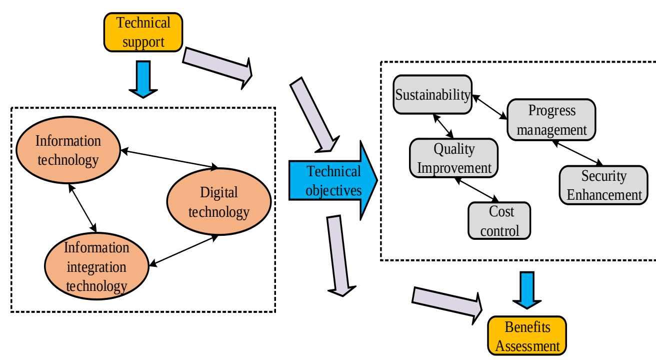


Fig. 1. Technical route of indicator system.

This study divides the indicators into five main dimensions, namely progress savings, cost savings, quality improvement, safety improvement, and sustainability improvement. Progress savings refer to improving the efficiency and accuracy of schedule management through intelligent construction technology. Cost savings are achieved through the application of technology to reduce unnecessary expenses and waste. Quality improvement is the use of BIM for tracking and managing construction materials and improving design quality. Security enhancement refers to the use of modern information technology to prevent major risks and enhance construction safety. Sustainability enhancement refers to providing decision-making support for environmental sustainability goals through modern information technology. These five dimensions are the primary indicators, and their division depends on three coordinate directions: time, technology, and sustainability goals. The reason why sustainability is listed as an important evaluation direction is because sustainable development includes internal elements such as energy conservation, green development, and digital development, and is the main development direction of smart buildings [17]. The main coordinate directions are shown in Fig. 2.

On this basis, multiple experts related to the field of smart construction are invited for expert discussions to provide professional opinions on preliminary indicators. By screening and refining indicators, comprehensive and implementable coverage of the indicators are ensured, and the secondary indicators are further expanded. The indicator system is listed in Table I.

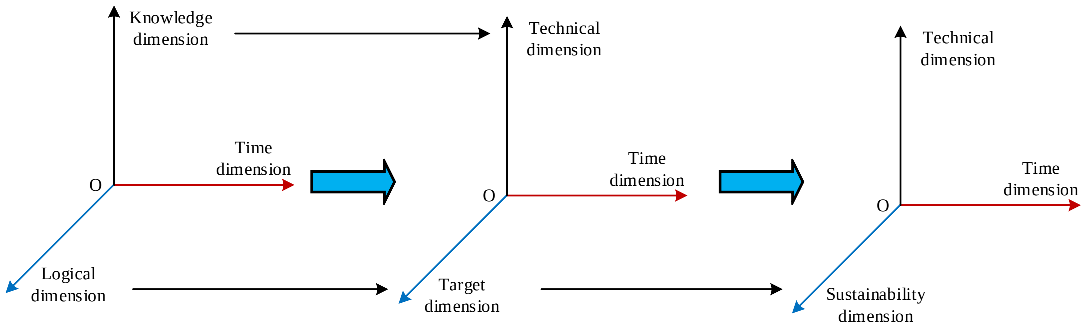


Fig. 2. Indicator dimension coordinate direction.

TABLE I. INDICATOR SYSTEM

| Serial Number | Primary indicators | Secondary indicators |
|---|---|---|
| A1 | Progress savings | Implementing time reduction in the design phase through BIM (ITRinDP through BIM) |
| A2 | | BIM technology saves construction time during the construction phase |
| A3 | | The benefits of 4D simulation in progress control during the construction phase |
| A4 | | Utilizing virtual reality to accelerate construction progress |
| B1 | Cost savings | The Application of BIM in Planning Land and Saving Costs |
| B2 | | Accurate measurement of cloud computing reduces design costs |
| B3 | | Design cost optimization based on BIM (BIM-based DCO) |
| B4 | | Improving construction cost management through cloud computing |
| B5 | | Utilizing big data technology to achieve cost optimization |
| B6 | | The role of BIM in reducing construction costs |
| B7 | | IoT technology saves costs in resource management (IoT saves RMC) |
| C2 | Quality improvement | BIM assists in tracking and managing construction materials (BIM assists TM-CMs) |
| C3 | | BIM application for improving the quality of design works (BIM-A for I-DWQ) |
| D1 | Safety improvement | The Application of Virtual Reality Technology in Risk Prevention |
| D2 | | Using cloud computing for early warning of construction safety |
| D3 | | The role of BIM in improving construction safety (BIMR in ICS) |
| D4 | | BIM's early warning function for construction safety hazards (BIM's EWF for CSH) |
| D5 | | Using Virtual Reality Technology to Strengthen Construction Safety |
| D6 | | The application of the Internet of Things in device security management |
| E1 | Sustainability improvement | The contribution of cloud computing in planning information sharing |
| E2 | | The advantages of BIM in saving materials and land resources |
| E3 | | BIM assisted planning and scientific decision-making process (BIM assists PSDP) |
| E4 | | The Promoting Role of GIS in Scientific Decision Making in Planning |
| E5 | | The energy-saving effect of the IoT in implementing green buildings (IoT-ESE in IGB) |
| E6 | | The improvement effect of big data in facility operation and maintenance management |
| E7 | | BIM improves efficiency in operation and maintenance management |
| E8 | | IoT technology enhances operational management efficiency |

In the secondary indicators, the progress management dimension includes dimensions such as design optimization progress savings, construction optimization progress savings, 4D visualization construction optimization progress savings, etc., to quantitatively analyze the impact of smart construction technology on project progress. The cost control dimension includes BIM planning land cost savings, cloud computing design precise calculation cost savings, BIM design optimization cost savings, etc., which can evaluate the cost management ability of smart construction technology. The dimension of quality improvement includes BIM construction material tracking management and BIM design quality improvement, which can reflect the status of intelligent construction improving the quality of engineering construction through information technology. The dimension of security enhancement includes indicators such as preventing major risks in virtual reality design and warning potential safety hazards in cloud computing construction, mainly targeting safety accidents. Under the dimension of sustainable development, it includes the improvement of cloud computing planning information sharing, BIM planning material and land conservation, and BIM planning scientific decision-making, focusing on the status of smart construction practices in environmental protection and resource efficiency.

### B. Application Strategy Design of C-WOA Operator

To effectively evaluate the SCB, this study proposes the C-OWA weighting method. This method minimizes extreme data in expert evaluations, reduces the potential negative impact of subjective bias, and accurately reflects the overall and differential nature of the data. Firstly, before constructing a weight allocation system, it is necessary to invite several experts to analyze the relevant indicators of the SCB. Table II shows expert information.

TABLE II. EXPERT INFORMATION TABLE

| Number | Unit nature | Educational Background | Years of Work Experience | Project Experience | Research Field |
|---|---|---|---|---|---|
| 1 | Research in universities | Doctor | Under 25 years | Not participating | Research on Architectural Theory |
| 2 | Construction and construction | Master | 5-10 years | Occasional participation | Construction project management |
| 3 | Building informatization | Undergraduate course | Over 10 years | Frequent participation | Intelligent management of construction process |
| 4 | Construction unit | Master | 5-10 years | Always participate | Architectural design informatization |
| 5 | Information support | Doctor | 5-10 years | Always participate | Software technical support |

On this basis, using a scoring method of 0 to 10 points, an expert team objectively evaluates indicators at the same level, and establishes an initial decision dataset, as shown in Formula (1).

$$a_i = \left\{a_1, a_2, \ldots, a_j, \ldots, a_n\right\} \tag{1}$$

Then, the dataset will be reordered to obtain a new dataset from high to low, which better reflects the importance of each indicator, as shown in Formula (2).

$$b_i = \left\{b_{0,} b_{1,} \ldots, b_{n-1}\right\} \tag{2}$$

Afterwards, weights are assigned to the values of the new dataset, and the combination number is used to determine the weights for different values, as shown in Formula (3).

$$\beta_{j+1} = \frac{c_{n-1}^{j}}{\sum_{k=0}^{n-1} c_{n-1}^{k}} = \frac{c_{n-1}^{j}}{2^{n-1}}, j = 0,1,2,\ldots,n-1 \tag{3}$$

In Formula (3), $c_{n-1}^{j}$ represents the number of combinations. The absolute weight obtained from weighting is Formula (4).

$$\overline{w_i} = \sum_{j=0}^{n-1} \beta_{j+1} b_j, i = 1,2,\ldots,m \tag{4}$$

In Formula (4), $b_j$ represents the weighted data. The relative weight is Formula (5).

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{m} w_i}, i = 1,2,\ldots,m \tag{5}$$

Afterwards, the absolute weights of each evaluation indicator are determined using the aforementioned weights and sorted scores, with the sum of all weights being 1.

### C. Design of Grey Cluster Evaluation Strategy

It is crucial to effectively measure the comprehensive benefits of smart construction projects in the evaluation process. To achieve this goal, researchers have proposed a quantitative method that can divide the benefits of smart construction into different levels and provide an evaluation system to quantify these benefits [18-19]. When designing the grey clustering evaluation strategy in this study, a set of evaluation systems is first constructed to quantify the building benefits, and a guiding approach is adopted to classify the SCB into four different levels: excellent, good, qualified, and poor. The SBBE level is Fig. 3.

However, in actual evaluation procedures, the SCB are often difficult to quantify and are easily influenced by personal subjective judgment and incomplete information [20-21]. To overcome this challenge, this study adopts the grey clustering evaluation method. Firstly, this study confirms the SCB at different levels and corresponding evaluation criteria. Each level has a corresponding score to represent the difference in benefits compared to traditional construction methods. Each benefit indicator has its own evaluation criteria, which helps to convert it into quantifiable data for subsequent analysis. Each benefit indicator will be rated by multiple experts, which form an initial evaluation matrix, as shown in Formula (6).

$$D_i = \left\{d_{ijk}\right\} s \times q \tag{6}$$

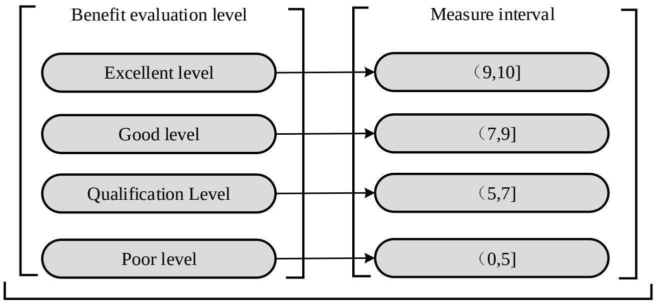


Fig. 3. Evaluation level of intelligent construction benefits.

In Formula (6), $d_{ijk}$ represents the expert rating. $k$ is the rating expert's serial number. $i$ represents the number of major indicators. $j$ means small indicator rating. $s$ is the total number of indicators. $q$ represents the total number of experts. Each gray class corresponds to an interval and function, quantitatively expressing the evaluation value at that level. The index evaluation coefficient is Formula (7).

$$X_{ije} = \sum_{k=1}^{q} f_e\left[d_{ijk}\right] \tag{7}$$

The total grey evaluation coefficient is Formula (8).

$$X_{ij} = \sum_{e=1}^{4} X_{ije} \tag{8}$$

To conduct a detailed evaluation, this study establishes a WWF. This function is used to convert expert ratings into a grey benefit evaluation index, which can reflect the distribution of benefit indicators on different grey levels. The grey number evaluation level is Fig. 4.

When the gray class e=1, the WWF is Formula (9).

$$f_1\left[d_{ijk}\right] = \begin{cases} d_{ijk}/4, d_{ijk} \in [0,4] \\ 1, d_{ijk} \in [4,\infty] \\ 0, d_{ijk} \notin [0,\infty] \end{cases} \tag{9}$$

When the gray class e=2, WWF follows Formula (10).

$$f_2\left[d_{ijk}\right] = \begin{cases} d_{ijk}/3, d_{ijk} \in [0,3] \\ 2 - d_{ijk}/3, d_{ijk} \in [3,6] \\ 0, d_{ijk} \notin [0,6] \end{cases} \tag{10}$$

When the gray class e=3, WWF is Formula (11).

$$f_3\left[d_{ijk}\right] = \begin{cases} d_{ijk}/2, d_{ijk} \in [0,2] \\ 2 - d_{ijk}/2, d_{ijk} \in [2,4] \\ 0, d_{ijk} \notin [0,4] \end{cases} \tag{11}$$

When the gray class e=4, WWF is expressed as Formula (12).

$$f_4\left[d_{ijk}\right] = \begin{cases} 1, d_{ijk} \in [0,1] \\ 2 - d_{ijk}, d_{ijk} \in [1,2] \\ 0, d_{ijk} \notin [0,2] \end{cases} \tag{12}$$

Obtaining the clustering weight vector based on the grey evaluation coefficient, as shown in Formula (13).

$$r_{ije} = \frac{x_{ije}}{x_{ij}} \tag{13}$$

Afterwards, a comprehensive grey clustering matrix is obtained by weighting each benefit indicator, as shown in Formula (14).

$$R_i = \begin{bmatrix} r_{i11} & r_{i12} & r_{i13} & r_{i14} \\ r_{i21} & r_{i22} & r_{i23} & r_{i24} \\ \vdots & \vdots & \vdots & \vdots \\ r_{in1} & r_{in2} & r_{in3} & r_{in4} \end{bmatrix} \tag{14}$$

The comprehensive clustering matrix is Formula (15).

$$M_0 = \left(M_1, M_2, \ldots, M_5\right)^T \tag{15}$$

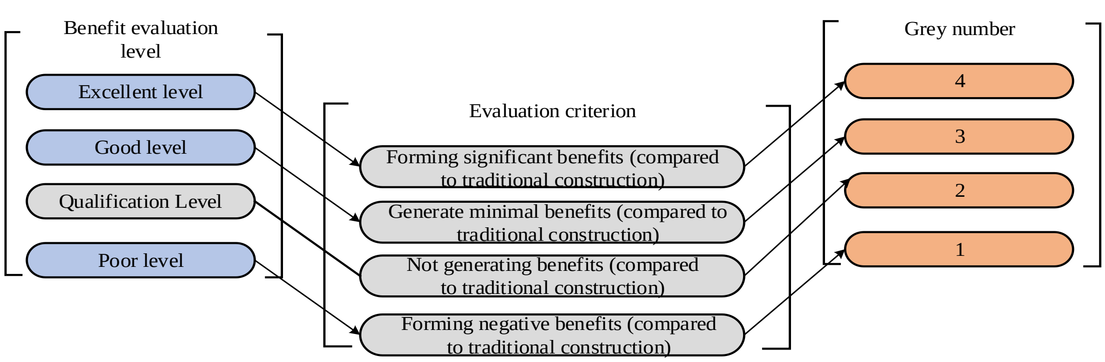


Fig. 4. Grey number evaluation level.

$M_n$ is calculated as Formula (16).

$$M_n = w_i \cdot R_i \tag{16}$$

The evaluation of primary indicators is as shown in Formula (17).

$$Z = W_0 \cdot M_0 \tag{17}$$

The grey evaluation coefficient of each indicator reflects the degree of evaluation of the grey category to which the indicator belongs in expert evaluation. Afterwards, by calculating the grey clustering weight vector and combining it with the weight matrix, a more refined comprehensive benefit evaluation can be obtained. The final step is to determine the overall value of the SCB based on the results of grey clustering and the set benefit measurement threshold, as shown in Formula (18).

$$U = \left(9.5, 8, 6, 2.5\right)^T \tag{18}$$

This value will determine the efficiency level of smart construction projects. The entire evaluation model aims to comprehensively cover all relevant indicators and accurately reflect the comprehensive SCB in various dimensions, as shown in Formula (19).

$$W = Z \cdot U \tag{19}$$

During the evaluation process, each indicator will be converted into a grayscale evaluation coefficient through the corresponding WWF. The evaluation coefficients are then summarized to form a comprehensive evaluation matrix. After weight calculation, this matrix will generate a clustering score for each evaluation indicator, thereby obtaining an objective measurement of the SCB.

## IV. Calculation of Index System Weights and Analysis of SCB

This study mainly analyzes the SCB analysis from three perspectives. The first is the reliability of the indicator system and whether the designed indicator system is reliable. The second is the calculation of indicator weights, analyzing the importance and priority of different indicators in overall SCB improvement. The third is SCB analysis, which mainly involves conducting practical evaluation and analysis.

### A. *Reliability Analysis of Indicator System*

In the reliability analysis of indicator systems, research has started from the perspectives of reliability and validity of indicators to test the reliability of the designed indicator system. Table III shows the reliability test results.

TABLE III. INDICATOR RELIABILITY ANALYSIS

| Number | Primary indicators | Secondary indicators | Correlation coefficient | Alpha Value | Is it for use? |
|---|---|---|---|---|---|
| A1 | Progress savings | ITRinDP through BIM | 0.758 | 0.923 | Yes |
| A2 | | BIM technology saves construction time during the construction phase | 0.762 | 0.936 | Yes |
| A3 | | The benefits of 4D simulation in progress control during the construction phase | 0.721 | 0.85 | Yes |
| A4 | | Utilizing virtual reality to accelerate construction progress | 0.744 | 0.878 | Yes |
| B1 | Cost savings | The Application of BIM in Planning Land and Saving Costs | 0.71 | 0.903 | Yes |
| B2 | | Accurate measurement of cloud computing reduces design costs | 0.675 | 0.847 | Yes |
| B3 | | BIM-based DCO | 0.732 | 0.81 | Yes |
| B4 | | Improving construction cost management through cloud computing | 0.759 | 0.832 | Yes |
| B5 | | Utilizing big data technology to achieve cost optimization | 0.718 | 0.892 | Yes |
| B6 | | The role of BIM in reducing construction costs | 0.782 | 0.909 | Yes |
| B7 | | IoT saves RMC | 0.765 | 0.887 | Yes |
| C2 | Quality improvement | BIM assists TM-CMs | 0.801 | 0.853 | Yes |
| C3 | | BIM-A for I-DWQ | 0.724 | 0.816 | Yes |
| D1 | Safety improvement | The Application of Virtual Reality Technology in Risk Prevention | 0.729 | 0.885 | Yes |
| D2 | | Using cloud computing for early warning of construction safety | 0.74 | 0.863 | Yes |
| D3 | | BIMR in ICS | 0.679 | 0.903 | Yes |
| D4 | | BIM’s EWF for CSH | 0.762 | 0.872 | Yes |
| D5 | | Using Virtual Reality Technology to Strengthen Construction Safety | 0.795 | 0.839 | Yes |
| D6 | | The application of the Internet of Things in device security management | 0.755 | 0.841 | Yes |
| E1 | Sustainability improvement | The contribution of cloud computing in planning information sharing | 0.777 | 0.862 | Yes |
| E2 | | The advantages of BIM in saving materials and land resources | 0.703 | 0.839 | Yes |
| E3 | | BIM assists PSDP | 0.812 | 0.894 | Yes |
| E4 | | The Promoting Role of GIS in Scientific Decision Making in Planning | 0.743 | 0.881 | Yes |
| E5 | | IoT-ESE in IGB | 0.788 | 0.908 | Yes |
| E6 | | The improvement effect of big data in facility operation and maintenance management | 0.815 | 0.876 | Yes |
| E7 | | BIM improves efficiency in operation and maintenance management | 0.825 | 0.869 | Yes |
| E8 | | IoT technology enhances operational management efficiency | 0.738 | 0.85 | Yes |

In Table III, the total alpha values of the five primary indicators are all greater than 0.7, indicating that the internal consistency of the test indicators is relatively high and meets the acceptance criteria. Table IV shows the validity test results.

In Table IV, generally speaking, a KMO value greater than 0.6 indicates high variable validity, and the KMO value of the indicator system studied is 0.843, indicating suitability for factor analysis. On the other hand, Bartlett's sphericity test is used to evaluate whether observed variables are independent of each other. The approximate chi square value of Bartlett's test is 1091.258, with 37 degrees of freedom and a significance level of 0.000, which is much smaller than any commonly used significance level. The indicator is fully effective.

## B. Calculation of Index System Weights

Due to the uncertainty of decision information in the decision-making process, the evaluation of comprehensive benefits often needs to consider the calculation of indicator weights.

TABLE IV. INDICATOR VALIDITY ANALYSIS

| Measuring Item | | Numerical value |
|---|---|---|
| KMO measurement value | | 0.843 |
| Bartlett sphericity test | Approximate chi square | 1091.258 |
| | Freedom | 37 |
| | Significance | 0.000 |

TABLE V. CALCULATION RESULTS OF INDICATOR WEIGHTS

| **Primary indicators** | **First level weight coefficient** | **Secondary indicators** | **Secondary weight coefficient** |
|---|---|---|---|
| Progress savings | 0.224 | ITRinDP through BIM | 0.273 |
| | | BIM technology saves construction time during the construction phase | 0.267 |
| | | The benefits of 4D simulation in progress control during the construction phase | 0.226 |
| | | Utilizing virtual reality to accelerate construction progress | 0.234 |
| Cost savings | 0.221 | The Application of BIM in Planning Land and Saving Costs | 0.135 |
| | | Accurate measurement of cloud computing reduces design costs | 0.147 |
| | | BIM-based DCO | 0.159 |
| | | Improving construction cost management through cloud computing | 0.141 |
| | | Utilizing big data technology to achieve cost optimization | 0.13 |
| | | The role of BIM in reducing construction costs | 0.158 |
| | | IoT saves RMC | 0.126 |
| Quality improvement | 0.163 | BIM assists TM-CMs | 0.472 |
| | | BIM-A for I-DWQ | 0.528 |
| Safety improvement | 0.199 | The Application of Virtual Reality Technology in Risk Prevention | 0.162 |
| | | Using cloud computing for early warning of construction safety | 0.149 |
| | | BIMR in ICS | 0.189 |
| | | BIM’s EWF for CSH | 0.183 |
| | | Using Virtual Reality Technology to Strengthen Construction Safety | 0.158 |
| | | The application of the Internet of Things in device security management | 0.154 |
| Sustainability improvement | 0.187 | The contribution of cloud computing in planning information sharing | 0.133 |
| | | The advantages of BIM in saving materials and land resources | 0.125 |
| | | BIM assists PSDP | 0.139 |
| | | The Promoting Role of GIS in Scientific Decision Making in Planning | 0.119 |
| | | IoT-ESE in IGB | 0.112 |
| | | The improvement effect of big data in facility operation and maintenance management | 0.118 |
| | | BIM improves efficiency in operation and maintenance management | 0.131 |
| | | IoT technology enhances operational management efficiency | 0.123 |

In Table V, in the dimension of schedule savings, "ITRinDP through BIM" has the highest weight coefficient of 0.273. Time management during the design phase is considered slightly more important. In the cost saving dimension, the weight coefficient of "BIM-based DCO" is the highest at 0.159, and the lowest in the same dimension is "IoT saves RMC" at 0.126. The difference in weight coefficients indicates that "BIM-based DCO" occupies an important position in overall cost savings, while IoT technology, although equally important, appears to have a slightly inferior position in overall cost savings strategy. In the dimension of quality improvement, the weight coefficient of "BIM-A for I-DWQ" is 0.528, significantly higher than the weight coefficient of "BIM assists TM CMs", which is 0.472. This indicates that in terms of quality improvement, BIM plays a more crucial role in improving design quality. In the dimension of security improvement, the weight coefficients of the four secondary indicators are relatively balanced, with only the weight coefficient of "BIMR in ICS" being 0.189, slightly higher than other indicators. This means that the application of AnBIM is slightly more prominent. Finally, in the dimension of sustainability improvement, the weight coefficient of "BIM assists PSDP" is the highest, at 0.139, indicating that in sustainable development, the role of scientific decision-making is more prominent than information sharing.

## C. SCB Analysis

This study focuses on a smart construction project in N city. The project consists of four buildings of different heights, with a total area of nearly 400000 square meters, including research and development, administration, dining, and other areas. Different buildings are connected by aerial bridges. When conducting project evaluation, the first step is to observe the WWF values of each indicator, which can be used to analyze the scores and excellence of indicators in different dimensions, and then evaluate the performance of the project in different aspects. Table VI shows the analysis of WWF values.

TABLE VI. ANALYSIS OF WHITENING WEIGHT FUNCTION VALUES

| Number | Primary indicators | Secondary indicators | Score | Range | centre | Good | Excellent |
|---|---|---|---|---|---|---|---|
| A1 | Progress savings | ITRinDP through BIM | 5 | 0.071 | 0.929 | 0 | 0 |
| A2 | | BIM technology saves construction time during the construction phase | 63.8 | 0.069 | 0.931 | 0 | 0 |
| A3 | | The benefits of 4D simulation in progress control during the construction phase | 51.1 | 0.917 | 0.083 | 0 | 0 |
| A4 | | Utilizing virtual reality to accelerate construction progress | — | 0 | 0.015 | 0.165 | 0.82 |
| B1 | Cost savings | The Application of BIM in Planning Land and Saving Costs | 87.1 | 0 | 0 | 0.79 | 0.21 |
| B2 | | Accurate measurement of cloud computing reduces design costs | 90.2 | 0 | 0 | 0.48 | 0.52 |
| B3 | | BIM-based DCO | 83.9 | 0 | 0 | 0.11 | 0.89 |
| B4 | | Improving construction cost management through cloud computing | 73.8 | 0 | 0.12 | 0.88 | 0 |
| B5 | | Utilizing big data technology to achieve cost optimization | 81.3 | 0 | 0 | 0.37 | 0.63 |
| B6 | | The role of BIM in reducing construction costs | 91.2 | 0 | 0 | 0.36 | 0.64 |
| B7 | | IoT saves RMC | 84.8 | 0 | 0 | 0.02 | 0.98 |
| C2 | Quality improvement | BIM assists TM-CMs | 76.8 | 0 | 0 | 0.8 | 0.2 |
| C3 | | BIM-A for I-DWQ | 85.6 | 0 | 0 | 0.94 | 0.06 |
| D1 | Safety improvement | The Application of Virtual Reality Technology in Risk Prevention | — | 0 | 0.215 | 0.511 | 0.185 |
| D2 | | Using cloud computing for early warning of construction safety | 72 | 0 | 0.709 | 0 | 0 |
| D3 | | BIMR in ICS | 88.4 | 0 | 0 | 0.648 | 0.352 |
| D4 | | BIM’s EWF for CSH | 86.2 | 0 | 0 | 0.872 | 0.128 |
| D5 | | Using Virtual Reality Technology to Strengthen Construction Safety | — | 0.111 | 0.889 | 0 | 0 |
| D6 | | The application of the Internet of Things in device security management | — | 0.123 | 0.877 | 0 | 0 |
| E1 | Sustainability improvement | The contribution of cloud computing in planning information sharing | 89.5 | 0 | 0 | 0.37 | 0.63 |
| E2 | | The advantages of BIM in saving materials and land resources | 85.7 | 0 | 0 | 0.94 | 0.06 |
| E3 | | BIM assists PSDP | 73.5 | 0 | 0.873 | 0 | 0 |
| E4 | | The Promoting Role of GIS in Scientific Decision Making in Planning | 88.1 | 0 | 0 | 0.371 | 0.629 |
| E5 | | IoT-ESE in IGB | 84.3 | 0 | 0.031 | 0.969 | 0 |
| E6 | | The improvement effect of big data in facility operation and maintenance management | 77 | 0.001 | 0.809 | 0.19 | 0 |
| E7 | | BIM improves efficiency in operation and maintenance management | 85.9 | 0 | 0 | 0.955 | 0.045 |
| E8 | | IoT technology enhances operational management efficiency | 90.4 | 0 | 0 | 0.365 | 0.635 |

In Table VI, in terms of cost savings, "IoT saves RMC" shows a prominent level of excellence with a high score of 84.8, significantly better than other secondary indicators. This high WWF value (excellent 0.98) intuitively reflects the effectiveness of IoT technology in optimizing resource allocation and cost control. Among the safety improvement indicators, the "BIM's EWF for CSH", which has a significant impact on construction safety, is particularly noteworthy. Its score reaches 86.2 points, and its excellence level is in the excellent level with a WWF value of 0.128, indicating that BIM has played a key role in preventing safety hazards. Under the primary indicator of sustainability improvement, the score of "IoT ESE in IGB" is 84.3, which is relatively good. The overall grey clustering evaluation matrix is Fig. 5.

In Fig. 5, the calculated comprehensive benefit value W is 8.342. According to the preset benefit level discrimination table, it indicates that the SCB of the project has reached a good level. This means that compared to traditional construction methods, the project has achieved a certain degree of benefit improvement, but has not achieved significant benefit improvement. In addition, by further analyzing the specific values of different benefit dimensions, the comprehensive evaluation values of progress savings W1, cost savings W2, quality improvement W3, safety improvement W4, and sustainability improvement W5 are 8.479, 8.424, 8.343, 8.335, and 8.343, respectively. The project has achieved a relatively balanced "good level" performance in different benefit dimensions, with the most significant benefits being the progress savings.

In Fig. 6, all primary indicators of the focused project have reached a good level, indicating an overall good state and no weaknesses in each indicator. Meanwhile, between 2021 and 2023, the comprehensive benefits show a stepwise upward trend. Finally, observing the changes in the rating time of the secondary indicators, the comprehensive benefits show a stepwise upward trend between 2021 and 2023, and the overall trend still shows an upward trend, reaching a good level in the end.

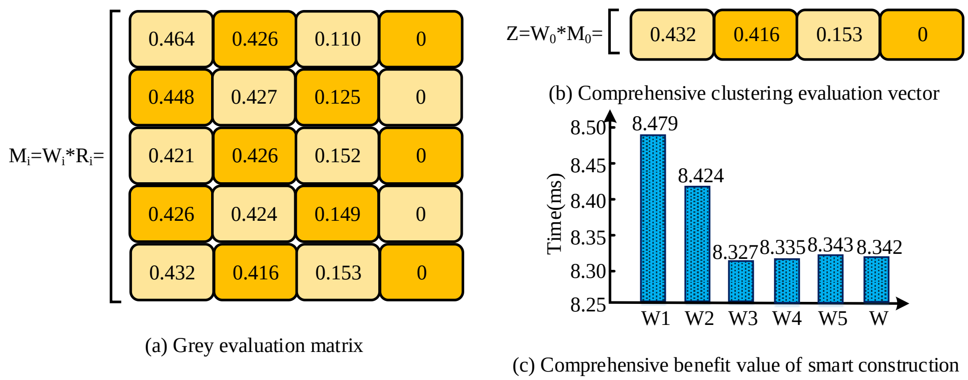


Fig. 5. Overall grey cluster evaluation matrix.

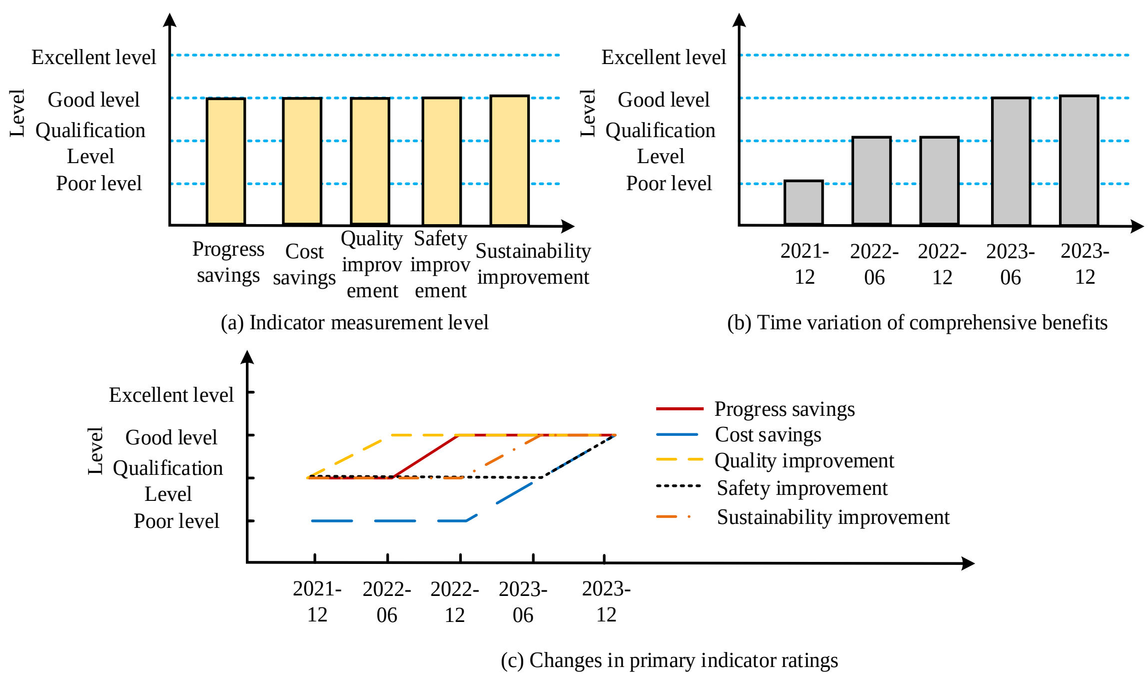


Fig. 6. Changes in project indicator ratings.

## V. Results and Discussion

The study combines the C-OWA operator with grey clustering method, and establishes an indicator system for evaluation objectives based on this. By forming a scoring matrix, standardized quantitative evaluation of the benefits of smart buildings can be achieved, and uncertain information in smart building projects can be evaluated. Through project application experiments, it was found that the indicator system designed in the study is reliable, and the KMO value and Bartlett's sphericity test have high significance. The indicator system designed in the study is effective. And in the actual application of smart building project evaluation, it can be found that the project has shown good performance in cost savings, safety improvement, and sustainability improvement, and the comprehensive benefits of the project have shown a stepped upward trend between 2021 and 2023, with a comprehensive benefit value of 8.342, reaching a good level. It can be seen that the C-OWA operator method used in the study can adjust the focus of project evaluation by flexibly adjusting weights, promoting the scientificity of smart building project evaluation. In addition, the research and design of the system can still provide more objective and accurate quantitative evaluation results in the face of uncertain information, which is more convenient for the standardization of industry benefit evaluation and the circulation of evaluation results, laying a foundation for the long-term development of the smart building industry.

## VI. Conclusion

This study constructed an evaluation system for SCB, and based on this, designed an evaluation method that integrates the C-OWA operator and grey clustering. This method was based on expert opinions and could efficiently quantify and analyze uncertain information. The results showed that in the evaluation system test, the total alpha value of internal consistency for five primary indicators exceeded 0.7, and the KMO value reached 0.843. The approximate chi square value of Bartlett's sphericity test was 1091.258, with a degree of freedom of 37 and a significance level of 0.000, demonstrating high reliability and validity. The weight coefficients of the primary indicators calculated through the C-OWA operator ranged from 0.163 to 0.224. Through project analysis, it could be concluded that the comprehensive benefit evaluation value of the project was 8.342, which was classified as a good level based on the level judgment. From a temporal perspective, the comprehensive benefits of this project had shown a stepwise upward trend between 2021 and 2023. Therefore, the comprehensive evaluation method for smart buildings designed is effective, which can objectively and comprehensively evaluate the extensive benefits of smart buildings and provide a data basis for project decision-making.

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