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A WCA-Based Evaluation Approach for Matching Analysis of the Construction Process

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Abstract: Assessing construction process optimization and efficiency is crucial for the industry, yet quantitative methods for comparison are lacking. We propose the process matching degree (PMD) to quantitatively assess construction processes, enhancing efficiency and sustainability. Five primary indicators—regulations, environment, equipment, components, and organization—were identified, each of which were initially weighted equally using the weighted criteria approach (WCA). To refine the assessment, we conducted a questionnaire survey to adjust these weights based on expert feedback. Three sub-indicators were introduced for each primary indicator to increase granularity. The PMD's operability was verified through two cases study involving BIM-simulated and real construction processes. The light-steel-structure building's PMD values were 68 and 58 points, and the concrete structure's PMD was 88.25, respectively, and the reasons for these differences were analyzed. This paper introduces PMD, its evaluation indicators, and calculation method, and verifies its feasibility through cases studies and expert questionnaire surveys, providing a comprehensive PMD research methodology.

Keywords: weighted criteria approach; deconstruction and reconstruction; process match degree; co-simulation; lightweight steel building

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1. Introduction

The construction process of a building has a significant impact on the environment [1,2], quality [3], cost [4], and schedule, and plays an important role in reducing environmental impact, ensuring quality, controlling cost, and improving schedule through optimization of the construction process. Therefore, project management (PM) plays a crucial role in ensuring the environmental impact, quality, costs, and schedule of building construction projects [5]. To achieve a smooth implementation, it is necessary to coordinate and balance these four aspects. The construction process, in particular, plays a vital role in this coordination. However, quantitatively studying construction processes has been challenging. Most construction schedules rely on the critical path method (CPM) schedules [6]. By linearizing the processes, comparing them with each other, and having response indicators for evaluation, we can instantly obtain information about the construction processes and their schedules, costs, and quality. The construction process and its schedule, cost, quality, and environmental impact can be obtained instantly. Efficient control, management, and evaluation of the differences between simulation and actual construction processes can enhance construction efficiency and lower construction costs. Many researchers had attempted to address the issue using various technological methods. For example, Ioannou et al. [7] presented a variance reduction technique based on dedicated and fully synchronized random number streams, the "matched pairs" method, which increased construction

efficiency from 55% to 95%, demonstrating the practical value of quantitative research on construction processes. Similarly, Eldeep et al. [8] studied the construction process lean management, and mentioned the importance of visualization for the construction process management and verified the importance of BIM, which is defined as a modeling technology and associated set of processes for producing, communicating, and analyzing building models. Through the application of BIM technology in the construction process, the design cycle can be shortened by 50%, and at the same time in the enhancement of the management of construction process, it shortens the real construction cycle by 1.5 months. Research in optimizing the construction process to enhance productivity also includes some of the following research literature. One study Chacón et al. [9] demonstrates how information pipelines and knowledge graph technologies can be utilized to enable continuous monitoring and analysis of the building construction process through a digital twin case study of a reinforced concrete frame structure of an office building. It also highlights its potential to improve productivity, resource efficiency, health, and safety in construction environments,but does not present a quantitative indicator of how much productivity is specifically improved by the relevant research. Similar studies about productivity enhancement through process management are also available. For example, Chen et al. [10] proposed a method for evaluating the productivity of the construction process through video data, analyzing the image data to form evaluation indexes for equipment, personnel, time, and trajectory, establishing a method for real-time evaluation of the process of the construction plant, and establishing the process monitoring and problem feedback (PMPF) framework. We also note that this paper introduces some related research literature on construction process quantification, which is valuable for our research on process quantification. Andrew Basta et al. [11] presented a BIM-based quantitative evaluation framework for deconstructing steel structures, which improved the deconstruction efficiency by accurately predicting the time and resources required for the process. This case highlights the practical benefits of applying quantitative evaluation methods to construction projects. Jia et al. [12] proposed a point cloud model based on multi-source geospatial data to realize a two-way interaction mechanism between BIM and the actual construction process, which provides an innovative methodology to ensure the quality of fine construction and improve the efficiency of building construction, and it inspired us to study the two-way interaction between BIM and the actual construction process, but the authors did not conduct a quantitative study of BIM and real construction process to compare the differences between them. Yilmaz et al. [13] developed the BIM Competency Assessment Reference Model (BIM-CAREM), which provides a systematic approach to assess BIM competencies for design, construction, and facilities management processes in the building industry, and helps organizations to more efficiently implement and improve BIM technologies, which in turn improves the efficiency of building construction processes and quality. Pfitzner et al. [4] captured the process of the construction site through image acquisition equipment, detected the construction process through image recognition technology, and built a knowledge graph of the various elements in the construction process, which gives us an idea to use the data acquisition technology through the acquired data to quantitatively evaluate the data compared with the detection data. Yang et al. [14] proposed a new framework for process management to address construction process optimization for prefabricated and cast-in-place components, by using IFC, flexible work break-down structure (WBS), and constraints-based simulation (CBS) methods. This scheduling framework can faithfully schedule the mixed construction process at different scale in a single BIM environment, and comparison with the traditional way shows it reduces the scheduling burden and improves the resource usage efficiency.

According to the above background, there are many studies focusing on construction processes, which are not listed due to the page limitation, but there is still not enough on how processes are quantified, although it is found through the research that optimizing processes and using new construction processes have an impact on cost, duration, quality, carbon emission, social environment, productivity, etc., but there is no quantitative indicator on construction processes research. Therefore, to determine whether there is an

evaluation indicator that can help us determine the variability and robustness of the process enhancement, we propose the concept of process matching degree (PMD) as a means to evaluate the differences between processes to optimize construction periods and reduce construction costs. However, the construction process of a building project is complex and varied, with many factors influencing the processes. It is therefore not feasible to determine the process variation based on a single factor. Therefore, there is a need for a research and development method capable of weighting multiple factors to evaluate the degree of process matching. To address this, we applied the weighted criteria approach (WCA) method to study the weighting of PMD. The research method of WCA includes the following steps:

1. Identify various influencing factors related to the research object, and determine their corresponding weight values based on their importance;
2. Classify the factors into different grades, from superior to inferior, and assign scores to each grade accordingly;
3. Summarize and multiply the contents of the sub-items within each influencing factor;
4. Multiply the weight of each factor by the weight of the factor;
5. Sort and multiply the corresponding weights of each factor;
6. Calculate the sub-score of each influential factor;
7. Add up the sub-scores to obtain the total score.

Once the PMD evaluation indicators were established, we conducted two case studies on a light-steel-structured building and concrete structure to assess the feasibility of our proposed methodology. Light-steel-structured buildings are widely used in construction due to their advantages, including their lightweight nature, long lifespan, ease of construction and deconstruction, and low carbon footprint. These procedures are closely related to various economic indicators of the project. Multiple factors influence processes, including regulations, the environment, equipment, components, and organization. We extract qualitative and quantitative indicators from these influencing factors and integrate them with BIM software to assess and quantify the differences between simulated and actual construction processes. To conduct comparative research on quantitative PMD indicators, we employ the following research methods:

(1) We analyze the influencing factors of both simulated and actual deconstruction and reconstruction processes;

(2) We introduce evaluation criteria, based on empirical analysis;

(3) We propose a method for calculating PMD.

Finally, we apply the procedure-matching evaluation method to actual light-steel-structure projects.

2. Literature Review

As mentioned in the above section, it is essential to begin with a literature review on the methodology of the WCA. This review helps us identify the relevant research methodology of the WCA and provide a theoretical basis for establishing the evaluation index of PMD. Furthermore, by studying construction processes, we aim to understand the current progress of research on the management, optimization, and evaluation of construction processes. Additionally, as we plan to conduct two case studies on a lightweight steel building and concrete structure building for the real PMD evaluation, it is crucial to determine whether there is existing research on the evaluation of related processes in the engineering management and simulated construction of light-steel-structure buildings.

2.1. The Studies of the WCA

The WCA is related to other multi-criteria decision-making (MCDM) methods such as the analytic hierarchy process (AHP) and the technique for order preference by similarity to ideal solution (TOPSIS). These methods consider the weights of various criteria during the decision-making process. However, they differ in terms of weight allocation, scoring methods, and ranking mechanisms. J. Sánchez-Garrido et al. [15] used the 38 characterization

indicators established by the MCDM technique to assess the sustainability life-cycle assessment of different modern methods of construction (MMC)-based building alternatives and proposed a global structural sustainability index (GSSI) to overcome the differences between the most commonly used decision-making techniques. In applying research related to the realization of sustainable construction in the context of demolition, Attia et al. [16] reviewed the contents related to the evaluation of disassembly buildings based on calculation criteria, and proposed the significance of potential for disassembly (PfD) for the development of sustainable buildings. Taylan et al. [17] utilized the fuzzy TOPSIS method to convert qualitative data into quantitative indicators, thus enhancing the accuracy of decision making. Zavadskas et al. [18] applied an improved MCDM methodology to construction project selection, integrating objective and subjective weights to enhance decision-making accuracy. Paramanik et al. [19] investigated the OSWMI method, which offers a new perspective on the MCDM problem by integrating objective and subjective weights to mitigate decision bias resulting from inconsistent weights. The method also considers the potential manipulation of weighting strategies. The OSWMI method reduces the likelihood of manipulation in the decision-making process, by deriving a combination of weights and rankings for alternatives. Lv et al. [20] introduced a target-level decision-making mechanism to enhance the single-objective MCDM process. This enhancement enables the spatial suitability evaluation to consider two conflicting decision-making objectives. As a result, a core set of dual-objective MCDM methods was developed. Past et al. [21] utilized the fuzzy analytic hierarchy process (FAHP) method in their study to assess the relative importance of different decision-making criteria, conducting pairwise comparisons and fuzzy logic, for determining the optimal treatment of construction and demolition waste in Tehran, Iran. Lao et al. [22] used a multi-objective optimization approach to enhance the design of the reinforcement layout for prefabricated components. They integrated the NSGA-II algorithm and the GD algorithm to achieve a balance between construction cost and feasibility. The method considered the two objectives: the construction feasibility score and construction cost. Abed et al. [23] conducted a study to determine inter-dependencies between criteria and indicators used to assess building sustainability. The study found that among the eight criteria considered for technical aspects, the materials and waste management (MW) and energy efficiency (EE) criteria carried the highest significance. This study contributes to the understanding of the relationships between criteria and indicators, which in turn will assist the development of new assessment tools for sustainable buildings. Dahooie et al. [24] utilized a weight determination method called CCSD (correlation coefficient and standard deviation) to enhance the performance of MULTIMOORA. By assigning distinct weights to each method, more realistic results can be obtained without relying on dominance theory. This approach also resolves problems associated with multiple comparisons and circular reasoning. Ayfokru et al. [25] introduced the realization of building construction process construction waste reduction through construction process lean management. Evaluation indexes of construction process waste were established by AHP to improve the level of lean construction.

As a multi-criteria decision-making tool, the WCA plays an important role in establishing the PMD. It helps decision makers identify and select optimal process combinations by rationally assigning weights and quantifying assessment criteria.The flexibility of the WCA allows it to incorporate different decision-making mechanisms, such as objective-level decision making and multi-objective optimization, to adapt to complex decision-making environments and the assessment needs of multiple conflicting objectives. Therefore, WCA is an effective method to improve the rationality and efficiency of PMD assessment and helps to achieve more efficient and sustainable construction process management.

2.2. Studies of Construction Processes

Many researchers have studied the processes of deconstruction and construction, with a primary focus on process simulation and optimization of actual processes. Sanchez et al. [26] aimed to facilitate the reuse of building components and materials by employing BIM to

simulate the deconstruction process. They developed suitable levels of development (LOD) models for components and materials. In terms of process optimization, Motahar et al. [27] proposed a hybrid method to optimize the disassembly sequence planning (DSP) for building reuse deconstruction processes, emphasizing three key factors: disassembly sequence time, cost, and environmental impact. This study provides valuable insights for evaluating process suitability. Sanchez et al. [28] proposed a rule-based recursive analysis method that aims to minimize environmental impact and disassembly costs, proving to be an effective alternative as it identifies near-optimal disassembly sequences by eliminating uncommon or impractical solutions. This study also emphasizes the importance of BIM models in analyzing factors like component independence, workspace availability, and resource location. Rauschetal [29] introduced a method that utilizes non-semantic CAD elements to automate key steps in the planning of architectural component disassembly. This method was demonstrated to be effective through case studies of real projects. The study stressed the importance of BIM model accuracy as a critical factor influencing the level of automation. Additionally, researchers have also explored the disassembly processes of mechanical components within the realm of mechanical engineering. Smith et al. [30] emphasized the importance of incorporating green design methods and considering disassembly costs in the overall design process, particularly during the end-of-life stages of the product life-cycle. They highlighted that during this phase, disassembly sequence planning plays a crucial role in end-of-life handling, highlighting cost as a significant influencing factor in deconstruction and construction processes. Rasmussen et al. [31] explored the implementation of circular design strategies in the construction industry, with a particular focus on the effects of upcycling and design for disassembly (DfD) on building sustainability. The study analyzed various issues related to the disassembly process in the design phase, and assessed their environmental impacts through the production, use, and demolition stages of a building's life-cycle. Denis et al. [32] developed a new method called disassembly network analysis (DNA) to quantify the impact of DfD in buildings and connect these impacts with specific design improvements. This study acknowledges that research on reusability is currently a prominent and relevant topic. Hradil et al. [33] introduced a new method for assessing the recyclability of components and structures in steel-frame buildings. They developed a program that calculates, weighs, and summarizes recyclability indicators to determine their potential for these elements to enter a second life-cycle. Desai et al. [34] studied end-of-life (EOL) goals for buildings, focusing on objectives such as component reuse, remanufacturing, and recycling, emphasizing the crucial importance of designing buildings for disassembly. Vassena et al. [35] proposed an innovative method for monitoring construction progress by integrating BIM-based construction scheduling (4D BIM) with periodic geometric surveying using an indoor mobile mapping system (iMMS). Sun [36] proposed a novel hybrid model called digital twin-building information modeling (DT-BIM). This model integrates various processes such as identifying resource shortages, analyzing requirements, making decisions, dispatching resources, and updating all processes in a database with the support of artificial intelligence (AI). Zhao et al. [37] developed an evidence-induced conceptual framework to assist stakeholders in their facility management decision-making processes. In terms of research on building processes and costs and carbon emissions, Heydari et al. [38] developed a BIM-based framework for evaluating costs and carbon emissions over the full life-cycle of a building, also emphasizing the impact of the construction process on costs and carbon emissions. Wu et al. [39] conducted a carbon assessment of two project cases and found a proportional relationship between the construction process and the building's carbon emissions, with machinery and equipment accounting for 90% of the carbon emissions in the construction process. The construction process includes a lot of safety factors. The realization of simulation process matching also needs to be associated with safe construction processes. There have been some studies on construction safety by studying the safety of the construction process, to avoid safety hazards, such as Morteza et al.'s [40] study of blockchain technology to establish a framework for the safety management of the construction process to achieve accessibility, traceability, and immutability. Barkokebas et al. [41] proposed a

digital methodology combining expert opinion and real-time sensor data to evaluate construction process improvements proposed in manufacturing environments by applying machine-learning algorithms and hypothesis testing, which is inspirational for improving the offsite construction (OSC) process, with an enlightening quantitative evaluation.

Existing studies have highlighted the key role of BIM in improving the PMD through simulation and optimization of deconstruction and construction processes, especially in terms of resource reuse, cost-effectiveness, and environmental impact assessment.

2.3. The Study of Assembly and Disassembly Process of Light-Steel-Structure Buildings

Light-steel-structure buildings are increasingly being used in temporary buildings due to their advantages, such as deconstructibility, simple conservation, and low carbon emission. Despite being temporary, these structures can have a long-lasting impact. This high degree of involvement enables researchers to carry out simulations of the construction process and the actual construction, leading to an optimized construction process. Obviously, researchers can significantly improve the progress, reduce costs, minimize energy consumption, and lower carbon emissions.

According to statistics, existing buildings account for 60% [42] of global energy consumption. Among these activities, the construction and demolition of buildings generate significant carbon emissions. Renovating and reusing existing buildings is a crucial strategy to reduce carbon emissions throughout the entire life-cycles of buildings. In a study by Huang et al. [43], they conducted a bibliometric analysis of literature on energy efficiency in existing buildings from 2008 to 2022 and aimed to identify future development trends and potential energy-saving directions for existing buildings throughout their entire life-cycle. The research suggests that implementing technological advancements is a powerful strategy for conserving energy in existing buildings. Selvaraj and Chan [44] examined the concept of achieving building reuse in a circular economy and proposed the design for construction and reuse method as a means to directly facilitate the reuse of building components. They emphasized that steel structures are particularly advantageous in this regard due to their easy disassembly, making them an important structural form for achieving a circular economy in the construction industry. Kitayama and Luorio [45] analyzed the current development status of steel structures, reviewed the current technological advancements, and anticipated a reduction in carbon emissions during building construction and demolition processes by emphasizing the importance of dismantling and reusing steel structural components to achieve this reduction in carbon emissions in the future. Danial et al. [42] developed a framework that integrates BIM technology with renovation categories. This integration enables more accurate and time-saving renovation activities to be carried out on existing buildings. Basta et al. [11] proposed a method called deconstructability assessment scoring (DAS) that quantitatively assesses the deconstructibility of steel structures, to encourage the reuse of steel structures. Hradius et al. [33] had developed a method for assessing the reusability of steel frame building components and structures. This method involves analyzing each building component, considering specific criteria to determine their suitability for reuse. Sanchez et al. [28] conducted a study on using the BIM model to assist in selective deconstruction processes. They proposed a multi-objective analysis method, which considers environmental, economic, and physical factors for selective deconstruction. By integrating these factors, the method aims to optimize the deconstruction process, enhance the social benefits of existing buildings, and minimize the environmental impact throughout the whole life-cycle of the building. Almasri et al. [46] investigated a methodology for work plan evaluation of lightweight steel structures in terms of cost, time, functionality, and sustainability, reflecting their own advantages and the significance of optimizing their construction.

The deconstruction and construction processes of buildings involve various factors that can affect the PMD of components. However, there is a lack of research on evaluating the PMD of components using the WCA. This paper aims to address this gap by providing a theoretical basis for calculating the PMD of building components using the WCA.

3. Methodology

The research methods employed in this study are designed to conduct comparative research on quantitative PMD indicators. Multiple factors influence construction processes, including regulations, the environment, equipment, components, and organization. We extract qualitative and quantitative indicators from these influencing factors and integrate them with BIM software to assess and quantify the differences between simulated and actual construction processes. The methodology consists of the following steps (Figure 1):

1. Analysis of influencing factors.

We begin by analyzing the influencing factors of both simulated and actual deconstruction and reconstruction processes. This analysis includes examining regulations, environmental conditions, equipment used, the components involved, and organizational factors that affect the construction process.

2. Introduction of evaluation criteria. Based on empirical analysis, we introduce evaluation criteria for the PMD. These criteria are derived from a detailed questionnaire survey, which was distributed to 20 experts in the field. The survey results provided insights into the relative importance of various factors, allowing us to establish initial weight values for each criterion.

3. Calculation of the PMD. We propose a method for calculating the PMD using the weighted criteria approach (WCA). Initially, equal weight values of 0.2 were assigned to each factor. These weights were then adjusted based on feedback received during the evaluation process. The detailed scoring system, which includes sub-factors and their respective weights and scores, is provided in Table 1.

4. Application to case study. Finally, we apply the procedure-matching evaluation method to an actual light-steel-structure project. This involves developing a detailed BIM model and conducting both real and simulated deconstruction and reconstruction processes. The PMD values are calculated for these processes, allowing us to compare and analyze the results.

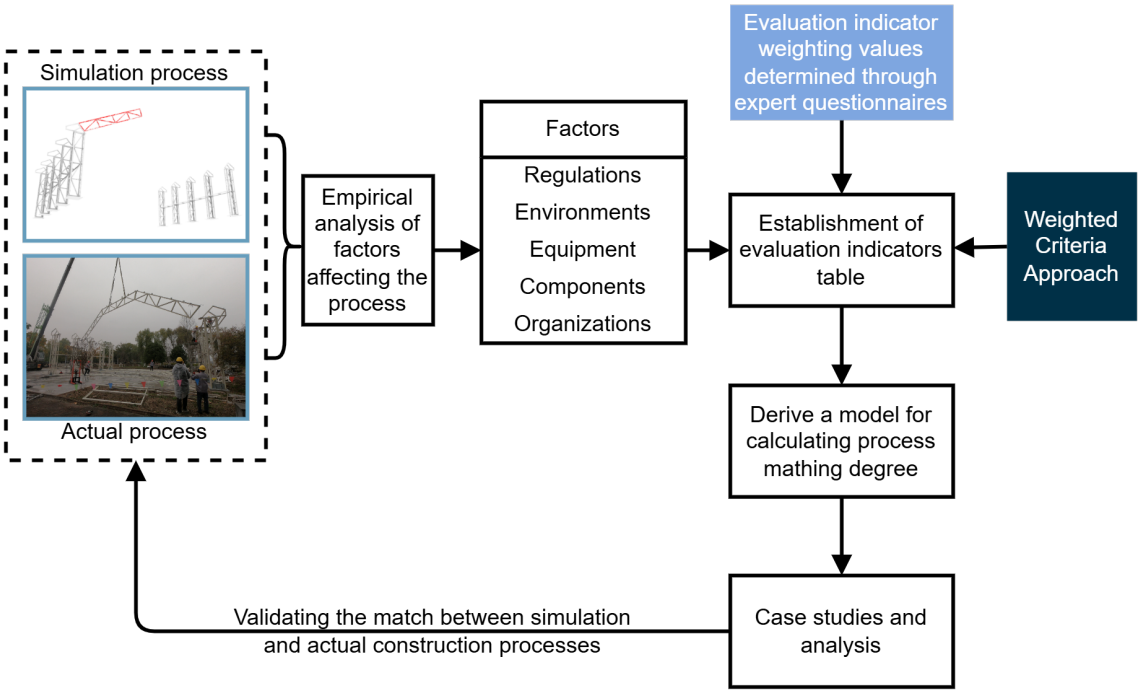


Figure 1. Research methodology and logical architecture diagram.

Table 1. Scoring table for the PMD of construction processes.

Evaluation Factors	Sub Factors	Weights and Scores	Contents
Regulations		$W_1 = 0.2$	
	Specifications	$S_{11} = 40$	Design specs., construction specs., acceptance specs., etc.
	Eco requirements	$S_{12} = 35$	Energy saving, carbon reducing, pollution controlling, etc.
	Other regulations	$S_{13} = 25$	Customs, religion, offensive behaviors, etc.
Environment		$W_2 = 0.2$	
	Geographic conditions	$S_{21} = 25$	Topographical features (slope gradient, elevation difference, etc.), geological conditions (soft or hard ground, soil quality, flooding, etc.), climatic conditions (cold, hot, rainy seasons, monsoon seasons, etc.), altitude, day–night cycles, and even gravitational or atmospheric conditions, etc.,
	Spatial limitations	$S_{22} = 50$	Height and width restrictions, man-made structures, natural landscapes, traffic, and, in rare cases, adding structures within buildings.
	Other limitations	$S_{23} = 25$	Weather (visibility, temperature, humidity, wind, rain, snow, sand, dust, etc.), informatization level, energy supply, etc.
Equipment		$W_3 = 0.2$	
	Lifting machinery	$S_{31} = 50$	Lifting capacity, boom reach, mobility, etc.
	Construction machinery	$S_{32} = 25$	Horizontal transport, machining equipment, power equipment, robots, etc.
	Construction tools	$S_{33} = 25$	Measuring, positioning, transferring, hand tools, labor protection, eco protection, monitoring and inspection, etc.
Components		$W_4 = 0.2$	
	Reuse plan	$S_{41} = 25$	Consider disassembly during installation, consider reuse on removal.
	Operability	$S_{42} = 50$	Stability, obstruction relations, operating space, temporary/permanent joints, etc.
	Other properties	$S_{43} = 25$	Existence state (corrosion, mold, cracks, softening or hardening, cleanliness, etc.), coating conditions, error control, etc.
Organization		$W_5 = 0.2$	
	Time constraints	$S_{51} = 35$	Project timeline requirements, working hours, etc.
	Labor allocation	$S_{52} = 35$	Personnel composition, technical level, high-altitude operations, etc.
	Other limitations	$S_{53} = 30$	Costs, construction methods, tech advancements, patents, etc.

3.1. Questionnaire Design and Weighting

3.1.1. Questionnaire Design

The questionnaire was designed to capture expert opinions on factors affecting construction processes and their respective weights in Appendix A. It included two main sections: Basic Information and Factors Affecting Construction Processes, to ensure a comprehensive understanding of the respondents' backgrounds and their expert evaluations.

1. Basic Information
   This section collected demographic data across four items to ensure a diverse representation of expertise. The questions included the type of company, professional title, field of expertise, and years of experience. These items were designed to categorize the respondents and assess the diversity and relevance of their professional backgrounds.
2. Factors Affecting Construction Processes
   This section focused on identifying and weighting factors that impact construction processes, comprising nine questions. Respondents were asked to select relevant factors, assign weights, specify sub-factor weights, suggest names for the evaluation index, and provide additional suggestions. This structure was chosen to gather detailed insights into the perceived importance and impact of various factors on construction processes.

3.1.2. Quantification of Responses

The responses were quantified using a weighted average approach. For each factor and sub-factor, weights assigned by respondents were normalized to sum to 100%, then averaged to determine final weights. This method ensures that the aggregated weights reflect the collective expert opinion while maintaining consistency across responses. We retracted the opinions of 20 experts, and the specific data are shown in the following Figure 2.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20
Q2-Regulations	20	26	15	17	35	30	20	20	30	40	30	31	40	40	40	20	25	15	8	20
Q2-Environment	20	14	10	17	10	10	20	20	10	40	20	25	20	20	20	20	20	10	20	21
Q2-Equipment	20	16	15	21	15	20	20	10	30	0	10	12	10	8	20	5	20	20	24	17
Q2-Components	20	21	25	20	10	10	20	10	10	0	20	8	20	12	0	20	10	20	6	20
Q2-Organization	20	21	31	11	30	30	20	40	10	20	10	24	10	17	20	32	25	30	38	22
Q2-Others	0	2	4	14	0	0	0	0	10	0	10	0	0	3	0	3	0	5	4	0
Q3-Coding and classification method	10	12	19	12	20	10	10	5	10	20	10	7	50	8	0	30	25	50	9	33
Q3-Construction-related standards	19	41	36	22	30	10	30	5	30	20	30	26	40	32	60	30	25	30	34	31
Q3-Relevant policies	6	19	28	36	40	30	35	40	40	20	25	36	10	25	40	10	30	10	26	21
Q3-Cultural influences	60	19	15	16	10	20	5	10	10	20	10	26	0	27	0	10	20	0	16	12
Q3-Other	5	9	2	14	0	30	20	40	10	20	25	5	0	8	0	20	0	10	15	3
Q4-Geographical conditions	8	20	31	35	25	25	25	60	30	20	20	33	30	48	40	30	30	5	41	26
Q4-Spatial limitations	49	38	27	32	60	50	50	20	30	20	30	25	30	35	40	30	25	20	29	35
Q4-Weather	17	24	13	23	15	20	15	10	20	20	20	37	10	12	20	20	30	70	25	22
Q4-Others	26	18	29	10	0	5	10	10	20	40	30	5	30	5	0	20	15	5	5	17
Q5-vertical equipment	12	22	33	19	50	50	50	50	30	20	40	31	35	30	40	30	25	30	25	24
Q5-construction equipment	45	39	28	35	20	30	25	25	30	20	30	33	35	32	60	30	30	30	44	21
Q5-construction tools	21	21	37	31	20	15	25	15	20	20	20	36	20	30	0	30	30	30	22	28
Q5-Others	22	18	2	15	10	5	0	10	20	40	10	0	10	8	0	10	15	10	9	27
Q6-Component reuse plan	16	17	23	26	40	20	35	40	40	20	30	17	50	40	0	20	15	40	12	26
Q6-Component maneuverability	56	30	35	17	40	40	40	20	30	20	30	24	25	29	40	40	30	30	47	21
Q6-Component connection nodes or	25	42	31	43	20	20	25	20	20	20	20	38	25	26	60	30	35	30	36	33
Q6-Others	3	11	11	14	0	20	0	20	10	40	20	21	0	5	0	10	20	0	5	20
Q7-Time constraints	23	24	32	22	40	10	35	30	30	20	30	37	40	42	40	30	25	30	14	20
Q7-Labor	17	41	24	27	35	50	35	45	20	20	30	19	30	25	40	30	30	50	44	19
Q7-Technological constraints	24	32	36	18	25	30	20	20	30	0	20	28	20	30	20	20	25	15	27	23
Q7-Others	36	3	8	33	0	10	10	5	20	60	20	16	10	3	0	20	20	5	15	38
Q8-Process matching degree	46	38	28	21	30	10	100	30	40	20	40	32	100	50	80	50	20	0	29	55
Q8-Process Coupling Rate	15	23	32	3	70	20	0	20	30	20	30	16	0	10	20	30	50	80	31	31
Q8-Process completion degree	17	29	23	41	0	70	0	30	20	20	15	22	0	40	0	10	30	0	16	11
Q8-Others	22	10	17	35	0	0	0	20	10	40	15	30	0	0	0	10	0	20	24	3

Figure 2. Data retrieved from the questionnaire survey.

3.1.3. Validation of Methodology

To validate the reliability and validity of our criteria and weights, we conducted reliability testing using Cronbach's α (Formula (1)). The calculated value was 0.895, indicating a very high level of reliability.

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{k}\sigma_2^i}{\sigma_{total}^2}\right) \quad (1)$$

where k identifies the number of questions in the measurement basis, σ_2^i denotes the variance of question i, and σ_{total}^2 denotes the variance of the overall score of the measurement tool.

3.2. Steps for Implementing PMD Evaluation

To further clarify the step-by-step process of the WCA and the scoring system for the PMD, the following steps outline the implementation:

3.2.1. Identifying and Categorizing Evaluation Factors

We identify the main evaluation factors, such as regulations, environment, equipment, components, and organization. Each factor is broken down into sub-factors, which are then scored based on their impact on the construction process.

3.2.2. Establishing Weight Values

Initial weight values for each factor are assigned equally (0.2 each). These weights are refined through a questionnaire survey and expert feedback to better reflect the actual influence of each factor.

3.2.3. Scoring System Development

For each sub-factor, specific scores are assigned based on their importance and relevance. The scores for each factor are then combined using the established weights to calculate the overall PMD value.

3.2.4. Data Collection and Analysis

Data are collected through both real and simulated construction processes. These data include detailed measurements, observations, and assessments of the construction activities.

3.2.5. Comparative Analysis

The PMD values for real and simulated processes are compared to identify discrepancies and areas for improvement. This analysis helps in validating the PMD methodology and its applicability to different construction projects.

By following these steps, we ensure a systematic and comprehensive approach to evaluating construction processes using the PMD. This methodology not only facilitates the assessment of current projects but also provides a framework for continuous improvement and optimization in construction management.

3.3. Influences of Simulated and Actual Construction Processes

The simulated construction sequence is an idealized plan, but it is nearly impossible to implement it perfectly in reality. It is common for there to be differences between the simulated and actual processes. These differences can be predicted by analyzing the factors that affect the construction process. Through experience-based analysis using the WCA, the influencing factors can be mainly categorized into five aspects: regulations, environment, equipment, components, and organization.

3.3.1. Regulations

Regulations play a crucial role in the construction industry, including codes, standards, policies, and cultural rules. Design codes and standards hold significant influence on the conception of the construction sequence, incorporating value-oriented aspects of process planning. It is important to note that variations in codes across different countries or regions can significantly impact the local construction industry. In addition, factors such as customs, religion, and offensive behavior may potentially invalidate construction sequence planning.

3.3.2. Environments

The environmental context in which construction activities take place plays a crucial role in shaping construction processes. To ensure accurate simulations, it is essential to incorporate site-specific characteristics, including terrain, geology, and climate, into the simulation framework. Before initiating construction, planners must carefully assess factors such as height and width restrictions, obstacles, and potential weather disruptions that may impact the project timeline. Furthermore, weather fluctuations can significantly impact the original construction plan, highlighting the importance of selecting favorable conditions whenever possible. A comprehensive understanding of these environmental

factors is crucial for informing construction planning decisions and mitigating potential risks and delays.

3.3.3. Equipment

Equipment plays a crucial role in the construction process, encompassing a diverse range of items such as construction machinery, temporary facilities, and hand tools. These components can significantly influence the sequence of component construction, as they are not permanent parts of the building and will be removed once the project is completed. Consequently, it is important to consider the impact of equipment on construction simulations to avoid discrepancies between simulated and actual scenarios.The capabilities of crane machinery, including lifting capacity, boom range, mobility, and other attributes, have a decisive impact on the construction sequence. Similarly, other types of construction machinery and tools can also exert a significant impact on the construction process.

3.3.4. Components

The characteristics of building components can significantly impact the construction sequence. One crucial consideration is whether the building is designed to be disassembled, as this affects the construction methods employed. The distinction between reversible and irreversible assembly methods, as well as reusable and destructive dismantling methods, can result in indistinct differences in construction sequence. Another key factor is the operability of the components, which encompasses considerations such as stability during construction, inter-blocking relationships, operational space, and the temporary nature of component connections. These factors, along with component properties such as their state of existence, painting condition, and error control, are crucial in determining the optimal construction sequence. Specifically, certain components may require prioritization or delayed operation due to their characteristics, which can pose challenges when inaccurately simulating their behavior.

3.3.5. Organizations

The organization of engineering resources, comprising time, labor, and cost, has a profound impact on planning construction processes. When project schedules are constrained, construction processes often need to be adjusted to shorten construction timelines. One of the primary considerations in determining the construction process is the daily working hours. Labor, being the most variable factor, requires careful consideration due to differences in personnel composition, technical expertise, and the need for specialized operations at high altitudes, which may require adjustments to the construction processes. Additionally, organizational factors including cost-related considerations and construction methodologies also play a role. However, these organizational factors are not always explicitly evident in actual or simulated construction processes.

3.4. Establish a Table of Evaluation Indicators Based on the WCA

The WCA requires assigning weights to each evaluation criterion based on specific project requirements. To accomplish this, we employed a combination of surveys and expert consultations, drawing on our collective engineering experience, to determine the relative importance of the five influencing factors. The resulting matching degree evaluation table is presented below, as shown in Table 1.

Based on the evaluation table, we derived the Formula (2) and developed a methodology for calculating matching degrees, utilizing the scoring data from the table.

$$Q = \sum_{i=1}^{5} \left(\sum_{j=1}^{3} S_{ij} \times W_i \right) \quad (2)$$

The formula computes a weighted sum (Q) of fifteen factors across five categories. Each category's weights add up to 1 and the maximum possible score is 100. The similarity between process sequences yields a score gain, while differences result in a loss. The resulting sum represents the PMD between the two processes.

3.5. Proposed Method for Calculating the PMD

To measure the reversibility of process sequences for each component during assembly and disassembly, the team proposed a PMD indicator and developed a formula for its calculation. The formula assesses the factors influencing process planning, assigning scores to each component based on the differences observed in each factor during construction, and computes the PMD through weighted summation. A PMD below 60% indicates that the construction processes for the component are not mutually reversible, requiring reevaluation of the removal sequence. The factors influencing the PMD across five categories—regulation, environment, equipment, components, and organization—along with their respective importance scores, are outlined in Table 1.

4. Case Study

In order to verify the validity and generalizability of the evaluation of the PMD, the PMD was measured for two types of case projects: light steel buildings and concrete structures built with ultra-high-performance concrete (UHPC) components.

4.1. Case 1: A Light Steel-Structure Building

4.1.1. Case Profile

Our team documented the deconstruction and off-site reconstruction process for a light-steel-structure building, utilizing BIM models and on-site records. The project, located in the Sipailou Campus of Southeast University courtyard (Figure 3), spanned 300 square meters and served as an outdoor activity space, teaching hub, and experimentation area. However, due to the renovation of the former School of Engineering, the building was relocated to Jiulonghu Campus (Figure 4). This project presented a fascinating research opportunity. By analyzing the construction process records, we verified the effectiveness and value of the PMD in evaluating the process through its application.



Figure 3. Project case before deconstruction site photo.



Figure 4. Project case after reconstruction site photo.

4.1.2. Case Study Architecture Diagram

According to the objective of the PMD study, we conducted a detailed study of the case, following a specific research process. The main steps of the process are outlined as follows: 1. we created a BIM model; 2. we identified and clarified the attribute types associated with the case; 3. we developed a plan to collect data during the construction process of the case; 4. we collected the required process data during the construction process, documenting each step and relevant factors; 5. the collected data were then evaluated using the PMD indicator; 6. we derived the calculation results, as shown in Figure 5.

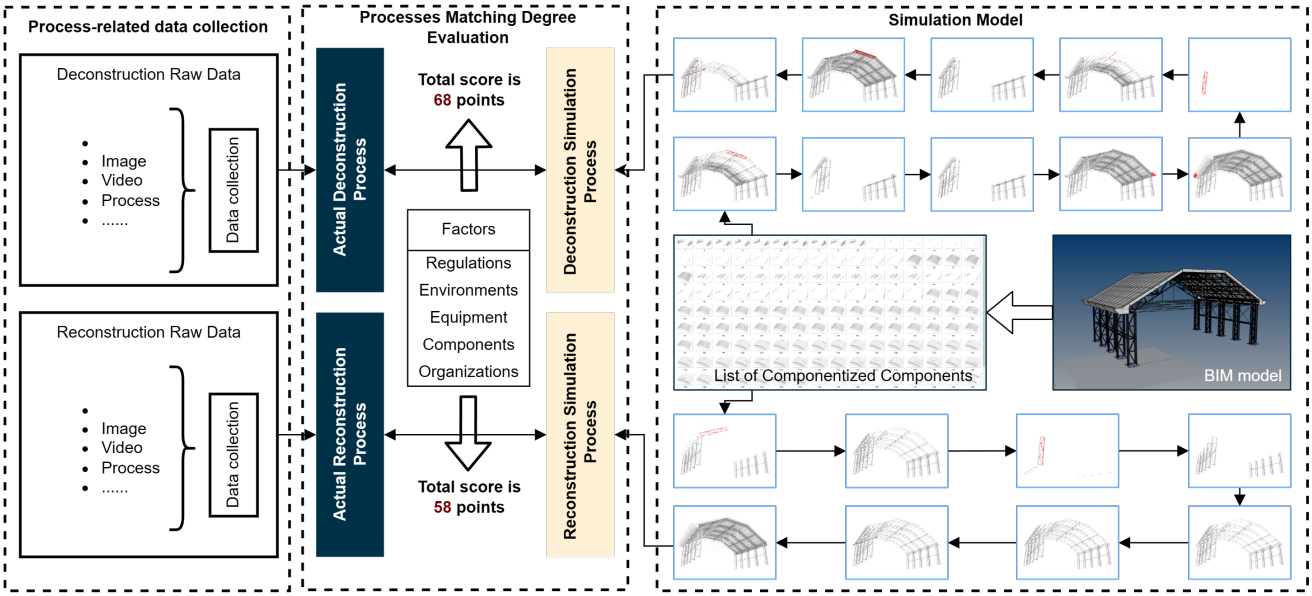


Figure 5. Case study architecture diagram.

4.1.3. BIM

To facilitate data monitoring and reprocessing during construction, as well as to enable virtual process simulation, a detailed 3D model was created (Figure 6) using Rhino 6 software. The model was carefully processed to demarcate and assign codes to each component, ensuring precise data tracking. This model serves as the basis for data processing and

provides the necessary conditions for calculating the PMD. Leveraging this model, we are able to simulate virtual construction processes (Figure 7), which in turn supports the calculation of the PMD.

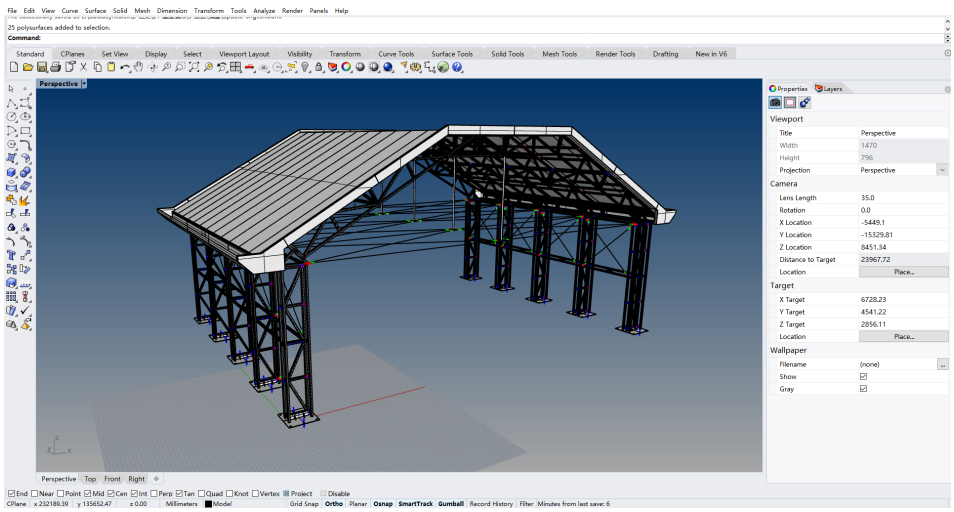


Figure 6. Model snap image.

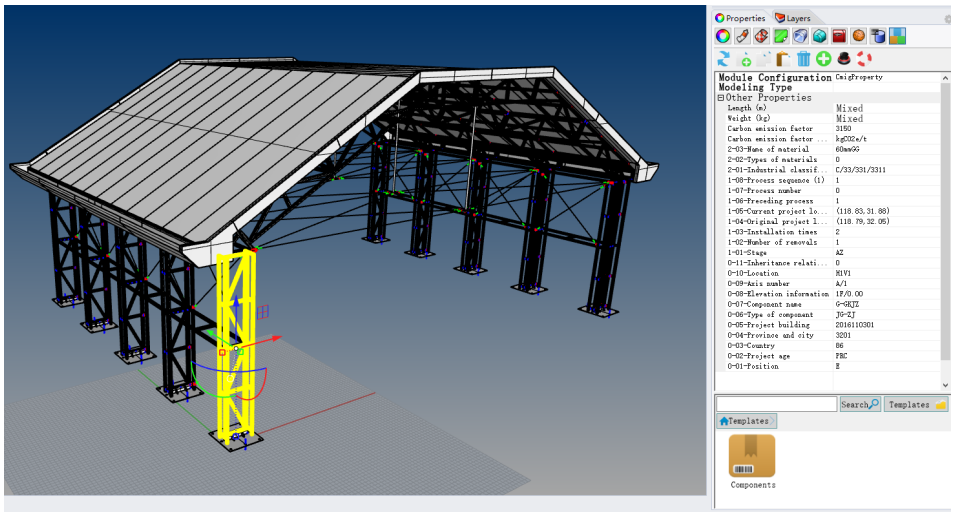


Figure 7. Model properties snap image.

To streamline data provision, we set up attributes for each component during BIM. This ensures a continuation of the calculations for subsequent automated process matching. The specific types of attributes included are as follows (Table 2):

Table 2. Properties.

No.	Property Name	Remarks
1	Length (m)	The length or height of the member.
2	Weight (kg)	Weight of the component.
3	Carbon emission factor	Combined carbon emission factor.
4	Carbon emission factor unit	Carbon emission factor unit.
5	0-01-Position	Project location.
6	1-01-Stage	Phase of the project.
7	1-03-Installation times	Number of project installations.
8	1-02-Number of removals	Number of times the project was dismantled.

Table 2. *Cont.*

No.	Property Name	Remarks
9	1-04-Original project location	Location of the project before dismantling.
10	1-05-Current project location	Location of the project after reassembly.
11	1-06-Preceding process	The process of the component prior to removal or reassembly.
12	1-07-Process number	Component number of the component removed or reassembled.
13	1-08-Process sequence	Sequence number of component removal or reassembly.
14	0-03-Country	The country where the project is located.
15	0-04-Province and city	Province and city where the project is located.
16	0-05-Project building	The building where the project is located.
17	0-06-Type of component	Type of component.
18	0-07-Component name	The name of the component.
19	0-08-Elevation information	Elevation information of the member.
20	0-09-Axis number	The axis number of the component.
21	0-10-Location	The location of the component.
22	0-11-Inheritance relationship	The inheritance relationship of the component.
23	0-02-Project age	The age of the project.
24	2-01-Industrial classification of national economy	The type of project according to the national economic sector classification.
25	2-02-Types of materials	Material type of the project.
26	2-03-Name of material	Material name of the project.

4.1.4. Deconstruction and Reconstruction Process Data Acquisition

We employed a GoPro camera to capture a sequence of images at 10-s intervals, to create a comprehensive visual record. This dataset served as the basis for subsequent data analysis and field situation assessments. Additionally, we can utilize this serialized image series to process video data and gather insights for editing the construction and reconstruction process video.

After collecting photo data from the site and processing them, we compiled a table to illustrate the deconstruction and reconstruction process. The primary objective was to compare and contrast the actual deconstruction with the simulated deconstruction (Table 3), as well as the actual reconstruction with the simulated reconstruction (Table 4). Although our data collection process did not encompass every single detail, we carefully selected a subset of data from one stage for analysis and comparison purposes.

Table 3. Component actual and simulation deconstruction data.

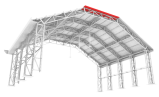
No.	Component Code	Component Type	Deconstruction No.	Deconstruction Method	Actual Photo	Simulation Screenshot
1	JSKB1	Baffle	1	Bolts		
2–21	……		2–21	Bolts		
22	JSKB22	Baffle	22	Bolts		
23	WMB1	Roof slab	23	Bolts		

Table 3. *Cont.*

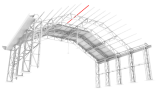
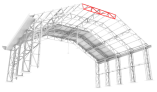
No.	Component Code	Component Type	Deconstruction No.	Deconstruction Method	Actual Photo	Simulation Screenshot
24–57	……		24–57	Bolts		
58	WMB36	Roof slab	58	Bolts		
59	G-GHJ1	Purlin	59	Bolts		
60–95	……		60–95	Bolts		
96	G-GHJ38	Purlin	96	Bolts		
97	SXLG1	Beam	97	Bolts		
98–130	……		98–130	Bolts		
131	G-GHJ35	Beam	131	Bolts		

Table 4. Component actual and simulation reconstruction data.

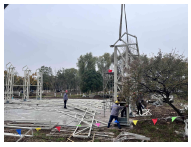
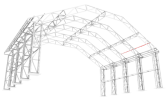
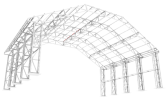
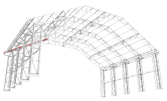
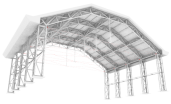
No.	Component Code	Component Type	Reconstruction No.	Reconstruction Method	Actual Photo	Simulation Screenshot
1	G-GKJZ1	Column	1	Bolts		
2–9	……	……	2–9	Bolts		
10	G-GKJZ10	Column	10	Bolts		
11	G-GHJ1	Beam	11	Bolts		
12–34	……	……	12–34	Bolts		
35	G-GHJ25	Beam	35	Bolts		

Table 4. *Cont.*

No.	Component Code	Component Type	Reconstruction No.	Reconstruction Method	Actual Photo	Simulation Screenshot
36	G-GHJ1	Purlin	36	Bolts		
37–72	……	……	37–72	Bolts		
73	G-GHJ38	Purlin	73	Bolts		
74	WMB1	Roof slab	74	Bolts		
75–108	……	……	75–108	Bolts		
109	WMB36	Roof slab	109	Bolts		

4.1.5. Validation of PMD Calculation Method

In our empirical study on lightweight steel buildings, we employed PMD indicators to predict whether the construction operations were inverse sequences.

The results are as follows.

1. Regulation factors: No changes were observed between deconstruction and reconstruction, resulting in a full score in this category.
2. Environmental factors: Deconstruction took place in an atrium with space limitations, while reconstruction occurred in an open space. This category scored 0, as there was no significant environmental impact.
3. Equipment factors: Propelled lifts were used during the deconstruction phase, while cranes and manual forklifts were employed during the reconstruction phase. As a result, there were no points for lifting machinery and other equipment. However, the construction tools remained consistent throughout the process.
4. Component factors: The operability of components varied based on their location during disassembly to ensure the stability of the building. However, the reuse plan remained consistent throughout the process. There were no other significant impacts on the processes from component properties, resulting in a score of 100 for this category.
5. Organization factors: The number of laborers and the requirement for high-altitude work changed between the deconstruction and construction phases, resulting in a score of 0 for this category. However, no special requirements were needed in terms of duration or working time, and the costs and construction methods remained unchanged throughout the process.

We calculated the PMD based on the above situation and formed the deconstruction process calculations (Table 5) and the reconstruction process (Table 6) calculations.

Table 5. The PMD of the key components in the disassembly processes.

No.	Component Code	Component Type	PMD
1	JSKB3	Eave board	68
2–21	……		……
22	JSKB3		68
23	WMB	Roof panel	68
24–57	……		……
58	WMB		68
59	G-GHJ4	Purlin	68
60–95	……		……
96	G-GHJ8		68
97	SXLG	Beam	58
98–130	……		……
131	G-GHJ2		58
132	G-GHJ	Column	68
132–140	……		……
141	G-GKJZ		68

Table 6. The PMD of the key components in assembly processes.

No.	Component Code	Component Type	PMD
1	G-GKJZ	Column	68
2–9	……		……
10	G-GKJZ		68
11	G-GHJ2	Beam	58
12–34	……		……
35	G-GHJ4		58
36	G-GHJ8	Purlin	68
37–72	……		……
73	G-GHJ8		68
74	WMB	Roof panel	68
75–108	……		……
109	WMB		68
110	JSKB3	Eave board	68
111–130	……		……
131	JSKB3		68

Upon analyzing the column, purlin, roof panel, and eave board components, we obtained the following scores:

- Regulations: specifications (40), eco requirements (35), other regulations (25)—Total: 100
- Environment: geographic conditions (25), spatial limitations (0), other limitations (25)—Total: 50
- Equipment: lifting machinery (0), construction machinery (0), construction tools (25)—Total: 25
- Components: reuse plan (25), operability (50), other properties (25)—Total: 100
- Organization: time constraints (35), labor allocation (0), other limitations (30)—Total: 65

The weighted summation resulted in a total score of 68 points.

In contrast, beam components scored:

- Regulations: specifications (40), eco requirements (35), other regulations (25)—Total: 100
- Environment: geographic conditions (25), spatial limitations (0), other limitations (25)—Total: 50
- Equipment: lifting machinery (0), construction machinery (0), construction tools (25)—Total: 25
- Components: reuse plan (25), operability (0), other properties (25)—Total: 50
- Organization: time constraints (35), labor allocation (0), other limitations (30)—Total: 65

The weighted summation resulted in a total score of 58 points, which falls short of the required 60 points.

The disparity in scores for beams can be attributed to the changes in stability during the processes of deconstruction and reconstruction. These results indicate that there are significant differences in the disassembly and assembly procedures for beams, affecting their overall PMD score. This prediction is supported by the construction process photographs, which clearly show distinct step-by-step variations between the disassembly phase (35 steps) and the assembly phase (25 steps).

4.2. Case 2: Concrete Structure Built with UHPC

4.2.1. Case Profile

Our team, in conjunction with the Inner Mongolia University of Technology, used BIM to design and construct a UHPC component building on its campus (as shown in the Figure 8), which was evaluated with the PMD.



Figure 8. Photos of completed construction.

4.2.2. BIM

We modeled the fine-scale model of the project using Rhino (Figure 9). Similar to case 1, where each component is accompanied by simulated and built properties information, and based on such a component model, the arithmetic and construction processes were simulated. This provided us with the conditions to perform the simulation of the PMD with the evaluation of real construction.

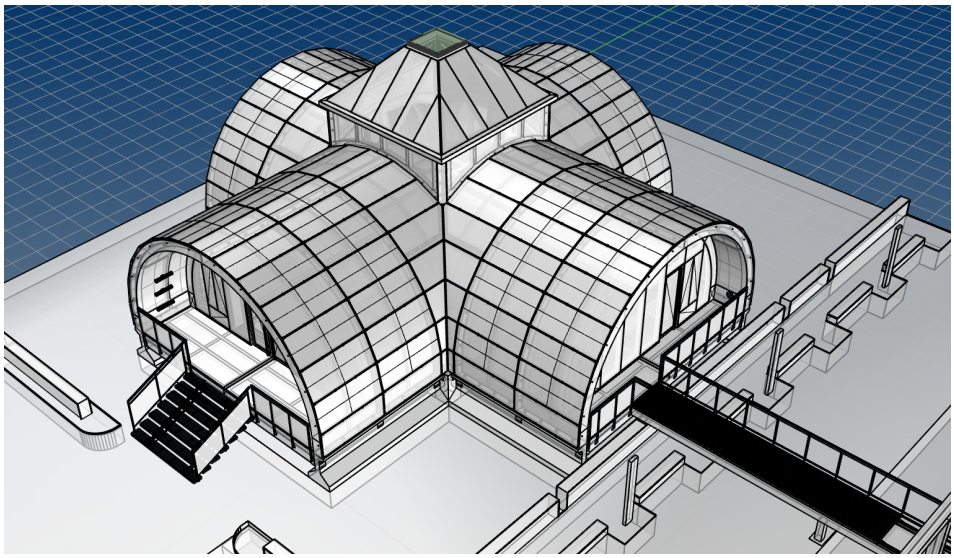


Figure 9. Screenshot of the model built in Rhino with all the component models and information.

4.2.3. Construction Process

Based on the BIM model, we simulated the construction process (Figure 10) and collected a large amount of construction data during the construction process (Figure 11). The evaluation object of the PMD is the comparison between the simulation and construction of components, so the comparison between the construction simulation of components in the BIM simulation environment and the data of components in the real construction process formed the basic elements of PMD evaluation. There are two points to be clarified: (1) since this project only has simulated and real construction, the evaluation table of the PMD only has the PMD indicators of the construction and assembly process; (2) the real construction process also includes component types such as rock wool panels, interiors, doors, and windows, etc., which we also simulated during the BIM simulation of the construction, but not all of them were collected during the actual construction process, so we mainly chose the resultant component types for the evaluation of PMDs, mainly including reinforced concrete foundation, UHPC flooring, UHPC Archwall, and UHPC Skylight.

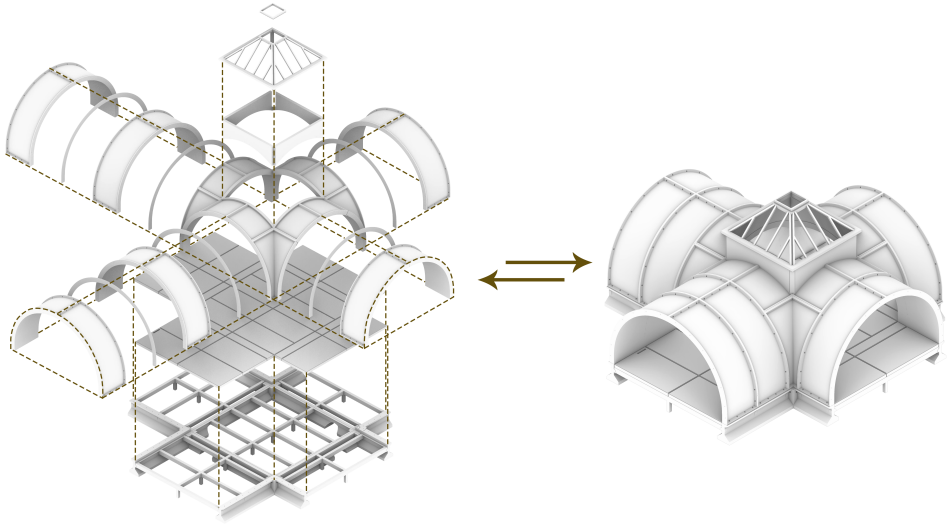


Figure 10. Some of the components were simulated and built by BIM.

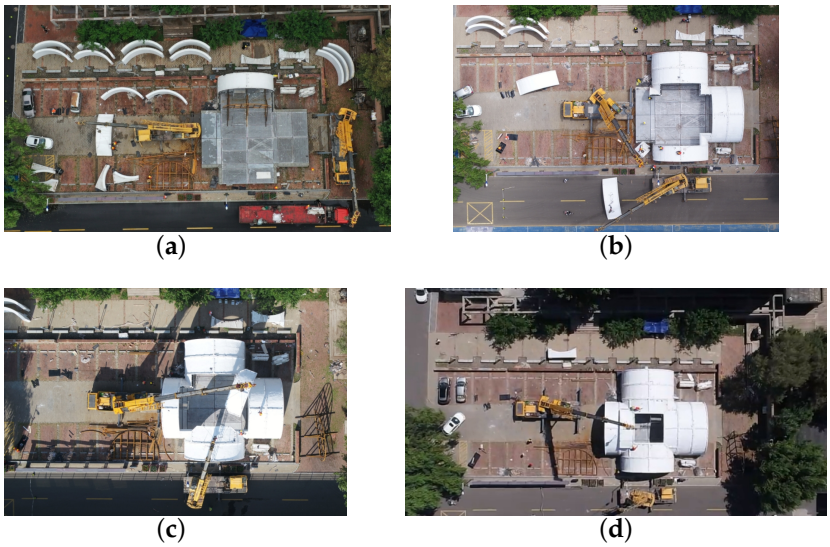


Figure 11. Partial aerial view of the construction process. (**a**) Transportation of components to site for trial assembly. (**b**) Assembly of east and north side components. (**c**) Assembly of west and south side components. (**d**) Assembly of skylight components.

4.2.4. Validation of PMD Calculation Method

1. Regulation Factors: For the regulation factors, the reinforced concrete foundation and UHPC Archwall both received a score of 75 due to partial compliance with regulations during both the deconstruction and reconstruction phases. On the other hand, the UHPC flooring and UHPC Skylight received full scores of 100, indicating complete compliance with regulations.
2. Environmental Factors:Regarding environmental factors, the reinforced concrete foundation and UHPC Skylight both achieved a full score of 100, as there were no significant environmental impacts noted in either phase. However, the UHPC flooring and UHPC Archwall each scored 75 due to some spatial constraints during the deconstruction phase.
3. Equipment Factors:For equipment factors, all component types (reinforced concrete foundation, UHPC flooring, UHPC Archwall, and UHPC Skylight) received full scores of 100. This is because consistent equipment usage was maintained throughout both deconstruction and reconstruction phases.
4. Component Factors:In terms of component factors, the reinforced concrete foundation and UHPC Skylight maintained their operability and scored a full 100. However, the UHPC flooring and UHPC Archwall scored 75 due to differences in component handling between the phases.
5. Organization Factors:Finally, for organization factors, the reinforced concrete foundation and UHPC Skylight received scores of 70 and 75, respectively, due to slight variations in labor and high-altitude work requirements. The UHPC flooring also scored 70 for similar reasons. In contrast, the UHPC Archwall showed improvement in organization and received a full score of 100.

Based on the evaluation of these factors, the final scores for the components are: reinforced concrete foundation, 89; UHPC flooring, 84; UHPC Archwall, 85; UHPC Skylight, 95, as shown in the Table 7, The average PMD for the four components was 88.25.

Table 7. The PMD of the key components in assembly processes.

No.	Component Code	Component Type	PMD
1	JC-AA-1	Reinforced concrete foundation	89
2–15	……		……
16	JC-AA-16		89

Table 7. *Cont.*

No.	Component Code	Component Type	PMD
17	DB-AA-1	UHPC flooring	84
24–42	……		……
43	DB-AA-28		84
44	GQ-AA-1	UHPC Archwall	85
45–63	……		……
64	GQ-AA-20		85
65	TC-AA-1	UHPC Skylight	95
66–67	……		……
68	TC-AA-4		95

4.3. Comparison of PMD Evaluation Results for Two Case Projects

After the PMD evaluation of these two case projects, we found that the evaluation score of Case 2 was higher than that of Case 1, and the following three reasons were analyzed: (1) the difference in the type of structure evaluated, as Case 1 is a light-steel-structure building type, with more types of component subdividing and a more detailed evaluation process, which led to a larger deviation between the simulation and the real construction process, while Case 2 was a concrete structure, with fewer types and a lower number of components, the evaluation was simpler and sloppier, and the match between the simulation and the construction process was indeed higher; (2) the difference in the construction form, as Case 1 includes the phases of deconstruction and reconstruction, and the components need to be considered for reuse after deconstruction is completed, which leads to a lower PMD score, and Case 2 has only the construction process, and therefore the object of the PMD evaluation is different, and there is no calculation of subsequent re-removal, which results in a higher PMD evaluation score; (3) a reasonable connection method difference, although the structure type difference will have an impact on the node connection difference during the construction process, but in Case 1, since the team designed and built the building in 2016 and completed the demolition and re-build process in 2023, some of the node connections designed back in 2016 were not convenient, while Case 2 was designed and built and completed in 2023, and the node connections, designed after several generations of design iterations, are simple and easy to operate, as well as suitable for BIM, which is the reason for the high PMD value of Case 2.

In summary, the validation process of the two cases may have deviated from the PMD calculation, but at the same time, they also show that the evaluation of PMD indicators can be realized for different structural types and connection types, and can respond to a certain extent to the situation of cost, efficiency, productivity, and design level.

5. Discussion

This paper investigates the problem of quantitative evaluation of the construction process and provides an evaluation method for assessing the differences in construction process sequences through PMD evaluation indicators established based on the WCA. Through a case study of a lightweight steel deconstructible building, we evaluated the PMD values of the deconstruction and reconstruction processes. The PMD values for the actual deconstruction and simulation processes were found to be 68 points, while the PMD value for the actual reconstruction and simulation processes was 58 points. Our average PMD evaluation result for Case 2 was 88.25, which is higher than Case 1. We note that changes in regulations, environmental conditions, and organizational factors significantly impact the construction process, highlighting the importance of having a dynamic PMD assessment tool.

Our findings are related to the broader context of construction management and sustainability, emphasizing the need for PMD as a complementary quantitative evaluation metric. The PMD provides a unique perspective for evaluating the consistency between simulated and real construction activities, thereby enhancing the decision-making process

for sustainable construction projects. The impact of the PMD on construction management is multifaceted, not only optimizing construction sequencing but also improving resource efficiency, reducing waste, and lowering construction costs.

However, it should be pointed out that although the PMD has the ability to promote the quantitative assessment of the construction process and the preliminary establishment of PMD evaluation indicators, the evaluation method, realized in the form of the WCA, and the evaluation results are relatively understandable through case validation, and there are still limitations in the current research on PMD:

1. Insufficient number of case validations: The current research relies on two case studies, which may not be sufficient to demonstrate the applicability of the PMD to a wide range of construction projects. This limitation suggests that more case studies are needed to comprehensively validate the PMD and promote the sustainability of construction projects across various contexts.

2. Indicator optimization: Although the initial indicators are established, and it is envisioned that the indicators and weights can be further optimized through subsequent research, there are limitations in the current approach to carrying out this optimization. The method for optimizing and expanding the research on PMD indicators needs to be developed further.

3. Applicability to different construction types: The current study focuses on a lightweight steel structure and concrete structure building, which may not represent the diverse range of construction types. Future research should explore the application of the PMD to various construction methods, such as wood structure, to ensure the generalizability and robustness of the PMD methodology.

Addressing these limitations in future research will involve:

1. Conducting additional case studies across diverse types of construction projects to validate the applicability and reliability of the PMD.

2. Developing methodologies for the reverse optimization of indicators, which will involve refining the indicators and their weights based on empirical data from various case studies. This process aims to improve the operability and effectiveness of PMD indicators in enhancing construction and management efficiency.

3. Expanding the application scope of PMD to include different construction methods, such as wood prefab and regular in situ construction. This will demonstrate the flexibility and adaptability of the PMD methodology across a broad spectrum of construction types.

6. Conclusion and Future Research

In this paper, we introduced the concept of the PMD and developed a WCA-based evaluation methodology to quantify the alignment between simulated and real construction processes, optimize the construction process to improve construction management efficiency, and achieve sustainable building goals. Through two case studies of a light-steel-structure building and concrete structure building, we demonstrated the feasibility and effectiveness of this approach in enhancing construction efficiency and sustainability. The PMD serves as a pivotal metric for assessing construction practices, offering a new dimension for quality control and process optimization.

The proposed PMD evaluation method has profound implications for the construction industry. It promotes a data-driven approach to construction management, enabling project teams to identify inconsistencies between planned and executed construction activities. This enables more informed decision-making, better allocation of resources, and a reduction in environmental impact. By integrating the PMD into industry practices, construction firms can enhance project outcomes, ensuring timely and cost-effective delivery while minimizing ecological footprint.

We envision the integration of the PMD evaluation method into BIM platforms, enabling real-time monitoring and adjustment of construction processes. This integration will provide practitioners with instant feedback on construction progress, facilitating proactive management of construction sites. Furthermore, the PMD can be utilized in

post-construction analysis, providing valuable insights for continuous improvement in construction methodologies.

While our study has laid the groundwork for the PMD evaluation method, there are several avenues for future research that can build upon our findings. These include:

1. Development of advanced PMD indicators: Further refining the PMD indicators to incorporate additional factors such as worker safety, quality control, and user satisfaction.

2. Integration with BIM and digital twin technologies: Exploring the technical requirements and challenges of integrating the PMD with BIM and digital twin technologies for enhanced process simulation and real-time monitoring.

3. Cross-industry application: Researching the potential applicability of the PMD method in other industries that involve complex construction or assembly processes, such as manufacturing or infrastructure development.

4. Regulatory and policy implications: Examining how the PMD method can inform regulatory frameworks and contribute to the development of construction standards and policies.

In future research, we will mainly go deeper into the following three aspects. (1) Perfect evaluation indicators to establish reverse indicators and weight optimization methods. The initial establishment of the PMD evaluation inevitably exists with limitations. There is a need to improve the accuracy of the evaluation during continuous updating in future research to establish the indicators of the reverse bidding and weight optimization methods and the formation of different versions of the evaluation, and to enhance the accuracy of the evaluation indicators of the PMD, promote the efficiency of the construction process, and realize the sustainable development of buildings. (2) Integration of new technologies to improve the efficiency of PMD evaluation. Front-loading the PMD evaluation, so that the pre-evaluation of PMD can be realized in the pre-design stage, and the construction efficiency can be improved through the optimization of the design to realize the sustainability of the construction. (3) Better support for the sustainability and life-cycle analysis. The construction process is not a particularly long stage in the whole life-cycle, but the quality of the construction process has an indispensable impact on the whole life-cycle. By extending the application of sustainability and life-cycle of PMD evaluation, the transformative potential of the PMD in advancing sustainable and efficient construction practices is highlighted.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Conflicts of Interest: Author Meng Cong was employed by the company Architects & Engineers Co., Ltd. of Southeast University. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Content of the Questionnaire

Appendix A.1. Questionnaire Forms

I. Basic Information

1. Type of your company: (Single choice)

(1) Investor company; (2) Survey and design company; (3) Construction company; (4) Supervision company; (5) Supplier company; (6) Scientific research and university; (7) Other companies

2. Your professional title: (Single choice)

(1) Assistant; (2) Intermediate; (3) Associate; (4) Senior

3. Your field of expertise: (Multiple choice)

(1) Design; (2) Construction; (3) Project Management; (4) Component Manufacturing; (5) Teaching and Research; (6) Others

4. Years of experience in your field: (Input)

II. Factors Affecting Construction Processes

1. What factors do you think are related to the construction processes? (Multiple choice)

(1) Regulations; (2) Environment; (3) Equipment; (4) Components; (5) Organization; (6) Others (please specify)

2. What do you think is the appropriate weight for these factors? (Input numbers, total should be 100%)

(1) Regulations; (2) Environment; (3) Equipment; (4) Components; (5) Organization; (6) Others (please specify)

3. In the category of regulations, which specific factors are relevant and what is their respective weight? (Multiple choice, total should be 100%)

(1) Coding and classification methods; (2) Construction-related standards; (3) Relevant policies; (4) Cultural influences; (5) Other (please specify)

4. In the category of environmental factors, which specific factors are relevant and what is their respective weight? (Multiple choice, total should be 100%)

(1) Geographical conditions; (2) Spatial limitations; (3) Weather; (4) Others (please specify)

5. In the category of equipment factors, which specific factors are relevant and what is their respective weight? (Multiple choice, total should be 100%)

(1) vertical equipment; (2) construction equipment; (3) construction tools; (4) Others (please specify)

6. In the category of component factors, which specific factors are relevant and what is their respective weight? (Multiple choice, total should be 100%)

(1) Component reuse plan; (2) Component maneuverability; (3) Component connection nodes or methods; (4) Others (please specify)

7. In the category of organizational factors, which specific factors are relevant and what is their respective weight? (Multiple choice, total should be 100%)

(1) Time constraints; (2) Labor; (3) Technological constraints (patents, new technology, etc.); (4) Others (please specify)

8. We aim to establish an evaluation index for construction processes to study the differences between simulated and real construction processes and improve construction efficiency. Which of the following names do you think is better?

(1) Process matching degree; (2) Process Coupling Rate; (3) Process completion degree; (4) Others (please specify)

9. Do you have any other suggestions for the study of quantitative indicators for construction processes? (Input)

Appendix A.2. Questionnaire Report

We received a total of 20 questionnaires. The respondents' characteristics conformed to a normal distribution, involving different types of companies, job title statuses, professional fields, and specific understanding of the factors influencing the construction process. The detailed distribution is as follows.

The pie chart in Figure A1 shows the distribution of company types that participated in the research survey. The largest segment, representing 25%, consists of construction companies, indicating their significant involvement and understanding of the construction process. Investor companies and scientific research institutions each make up 15% of the

respondents, highlighting their roles in funding and researching construction processes. Supplier companies also account for 15%, reflecting their importance in providing materials and equipment. Survey and design companies and supervision companies each constitute 10%, representing their responsibilities in design and oversight. The remaining 10% comprises other companies. This diverse participation ensures a comprehensive analysis of the factors influencing construction processes, making the survey results robust and representative.

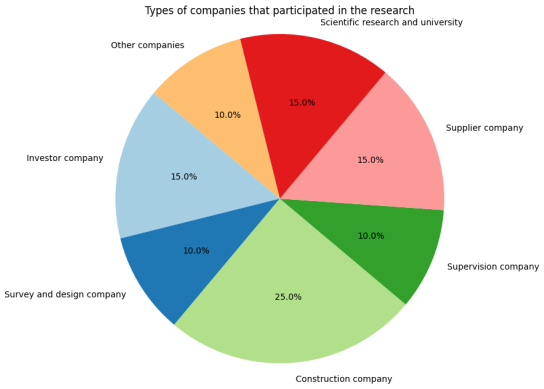


Figure A1. Types of companies that participated in the research.

The pie chart in Figure A2 shows the distribution of professional titles among the survey respondents. The largest group, at 45%, holds intermediate titles, indicating that nearly half of the respondents are in mid-level positions. Associate titles are held by 40% of the respondents, demonstrating a significant proportion of participants with an advanced level of expertise. Assistant titles account for 10%, reflecting a smaller group of entry-level professionals. Senior titles are the least represented, at 5%, indicating a limited number of high-level professionals among the respondents. This distribution provides insight into the varied levels of professional experience and expertise in the survey sample.

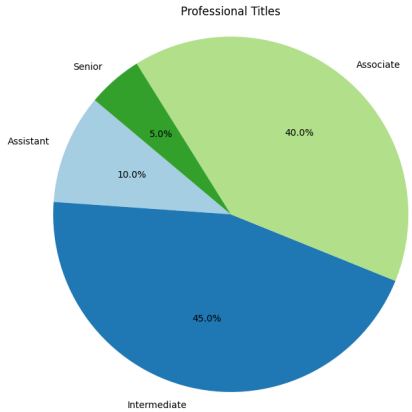


Figure A2. Professional titles.

This pie chart (Figure A3) shows the distribution of professions practiced by the survey respondents. The largest segment, representing 28.6%, is engaged in project management, indicating a significant focus on overseeing and coordinating construction projects. Design professionals make up 21.4% of the respondents, highlighting the importance of planning and architectural aspects. Both construction and component manufacturing professions each account for 17.9%, emphasizing the practical and production sides of the industry. Teaching and research professionals comprise 10.7%, reflecting their role in education and

innovation, while the remaining 3.6% are involved in other unspecified professions. This distribution demonstrates the diverse range of expertise and roles within the construction industry.

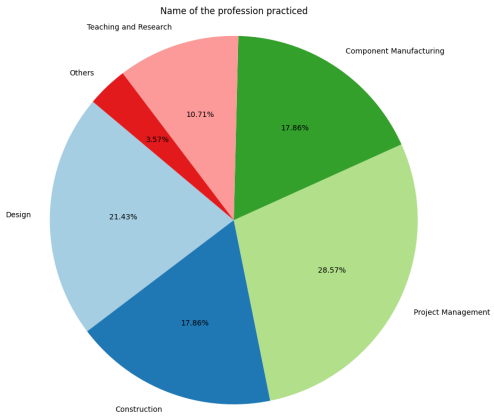


Figure A3. Name of the profession practiced.

This bar chart (Figure A4) shows the years of professional work experience among the respondents. It shows that the majority, 12 respondents, have 10–20 years of experience, indicating a well-established mid-career group. Those with over 20 years of experience make up the second-largest group with six respondents, highlighting a significant presence of highly experienced professionals. Lastly, only two respondents have 1–10 years of experience, suggesting fewer early-career participants in the survey.

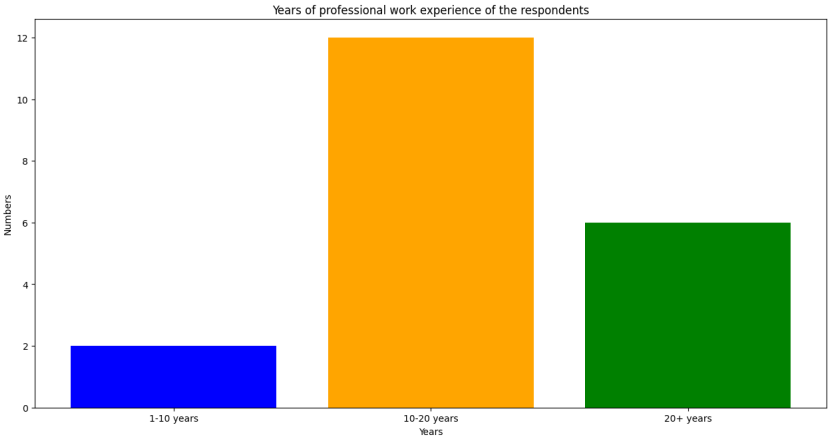


Figure A4. Years of professional work experience of the respondents.

This pie chart (Figure A5) shows the factors affecting the construction process as identified by the survey respondents. The largest factor, accounting for 23.1%, is regulations, indicating the significant impact of rules and standards on construction activities. Organization and environment both contribute 20.5% each, emphasizing the importance of project management and external conditions. Equipment is considered a factor by 17.9% of respondents, reflecting the role of machinery and tools. Components, which are the actual building materials, account for 15.4%. Finally, other unspecified factors make up 2.6% of the total, showing that while regulations, organization, environment, equipment, and components are the primary considerations, there are additional influences at play.

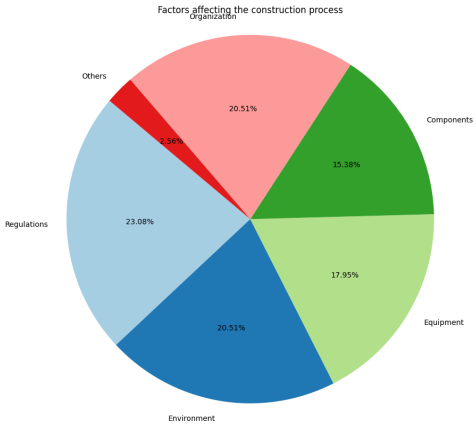


Figure A5. Fractors affecting the construction process.

This pie chart (Figure A6) shows the weighting of various factors influencing the construction process. The most significant factor is regulations, accounting for 26.1% of the total influence. Environment follows with 18.4%, and organization comes in at 23.0%. Equipment and components have similar weightings at 15.6% and 14.1%, respectively. A minor portion, 2.7%, is attributed to other factors. This distribution highlights the multifaceted nature of influences affecting construction processes, with regulations and organizational aspects playing prominent roles.

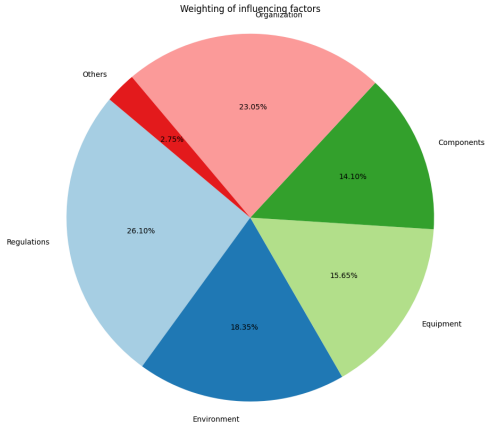


Figure A6. Weighting of influencing factors.

This pie chart (Figure A7) shows the content and weighting of various factors influencing regulations. The most significant factor is construction-related standards, accounting for 29.0% of the total influence. Relevant policies follow with 26.3%, and coding and classification methods come in at 17.5%. Cultural influences have a weighting of 15.3%, while other factors make up 11.8%. This distribution highlights the importance of construction-related standards and relevant policies in shaping regulatory frameworks, with coding methods and cultural influences also playing significant roles.

This pie chart (Figure A8) shows the content and weighting of various factors influencing environmental aspects. The most significant factor is spatial limitations, accounting for 33.8% of the total influence. Geographical conditions follow with 29.1%, and weather comes in at 22.1%. Other factors have a weighting of 15.0%. This distribution highlights the importance of spatial and geographical considerations in environmental influences, with weather conditions also playing a notable role.

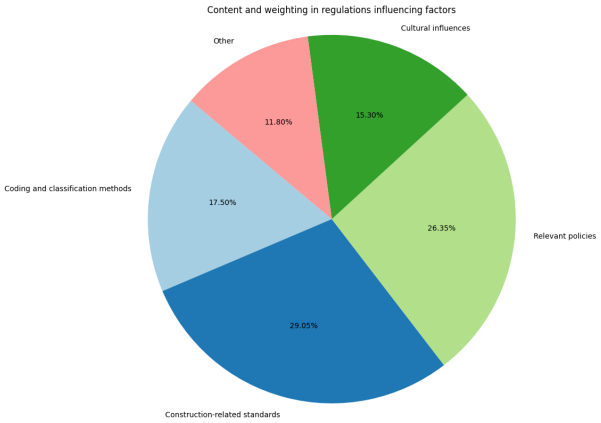


Figure A7. Content and weighting in regulations influencing factors.

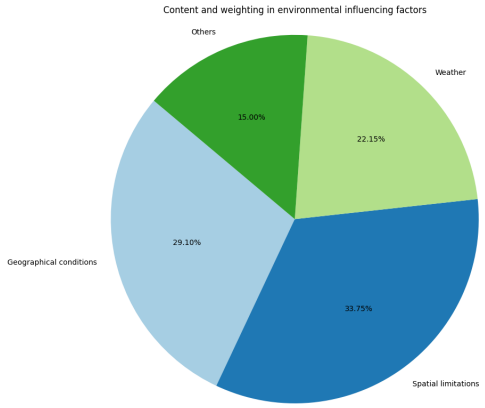


Figure A8. Content and weighting in environmental influencing factors.

This pie chart (Figure A9) shows the content and weighting of various factors influencing equipment aspects. The most significant factor is vertical equipment, accounting for 32.3% of the total influence. Construction equipment follows closely with 32.1%, and construction tools come in at 23.5%. Other factors have a weighting of 12.0%. This distribution highlights the prominent roles of vertical and construction equipment in influencing equipment-related aspects.

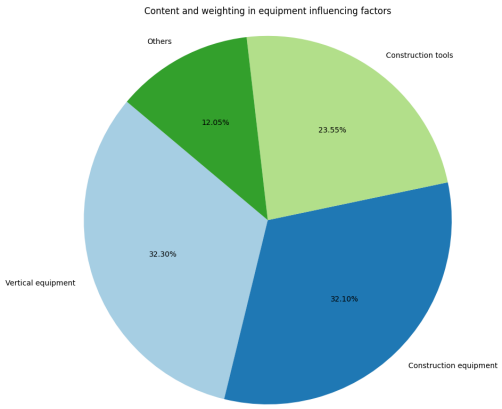


Figure A9. Content and weighting in equipment influencing factors.

This pie chart (Figure A10) shows the content and weighting of various factors influencing components. The most significant factor is component maneuverability, accounting for 32.2% of the total influence. Component connection nodes or methods follow with 30.0%, and component reuse plan comes in at 26.4%. Other factors have a weighting of 11.5%. This distribution highlights the importance of component maneuverability and connection methods in influencing component-related aspects.

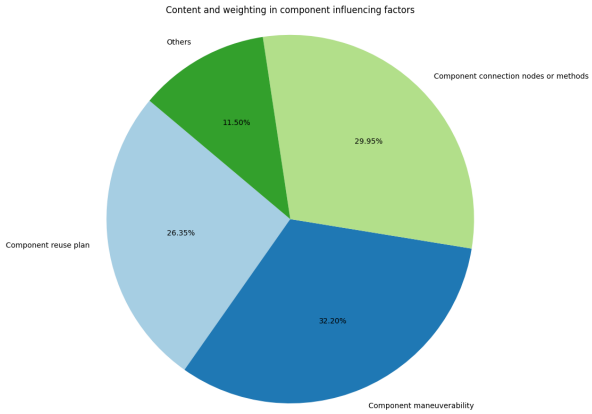


Figure A10. Content and weighting in component influencing factors.

This pie chart (Figure A11) shows the content and weighting of various factors influencing organizational aspects. Labor is the most significant factor, accounting for 31.5% of the total influence. Time constraints follow with 28.7%, and technological constraints (such as patents and new technology) contribute 23.1%. Other factors have a weighting of 16.6%. This distribution highlights the importance of labor and time constraints in organizational influence, with technological constraints also playing a significant role.

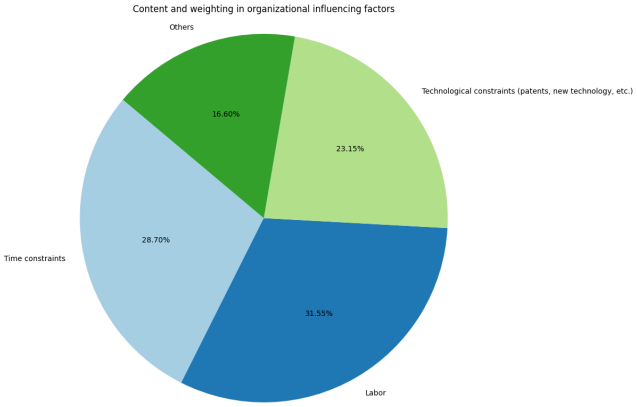


Figure A11. Content and weighting in organizational influencing factors.

This pie chart (Figure A12) shows the weighting of various quantitative indicators for the construction process. The process matching degree is the most significant factor, accounting for 41.0% of the total influence. The process coupling rate follows with 26.5%, and the process completion degree contributes 19.7%. Other factors have a weighting of 12.8%. This distribution highlights the importance of the process matching degree and coupling rate in evaluating the construction process, with the completion degree also playing a notable role.

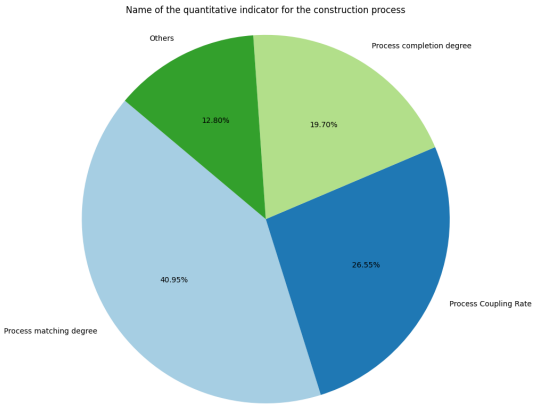


Figure A12. Name of the quantitative indicator for the construction process.

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