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Maturity Assessment of Intelligent Construction Management

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Abstract: In the new era of Construction 4.0, the application of a large number of intelligent information technologies (ITs) and advanced managerial approaches has brought on rapid development of Intelligent Construction Management (ICM). However, it is still unclear about how to assess the maturity of ICM. In this study, a maturity assessment system for ICM is formulated through literature reviews, questionnaires, expert discussions and a case study. A maturity scoring table containing five assessment dimensions and twenty assessment indicators is developed and corresponding maturity levels and a radar chart of dimensions are designed. A case study of the assessments of two construction enterprises is conducted to validate that the proposed assessment system can be used by construction enterprises to quantitatively assess their ICM maturities and get both overall and specific assessment results. This study also proposes practical improvement methods to improve ICM maturities for construction enterprises with different maturity levels. Furthermore, the study also discusses the development direction of ICM at present and in the short-term future, which should be paid more attention to by the construction industry.

Keywords: Intelligent Construction Management (ICM); construction industry; maturity assessment system; improvement plan

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1. Introduction

The construction industry is a traditional pillar industry in many countries, its contribution to economic growth and long-term national development is widely acknowledged [1]. In China, for example, the construction industry contributed about 25.6% to the national Gross Domestic Product (GDP) in the year of 2021 [2]. However, the construction industry involves a large number of participants and covers multiple professions so that the improper and bad management of any aspect often causes huge losses. The fatal injury rate for the construction industry is higher than the average for all industries due to its labor-intensive characteristic and poor safety management during production processes [3]. Careless quality management will cause a hidden danger to the later operation of structures. Many construction projects worldwide were completed with significant time and cost overruns due to bad schedule management [4]. Furthermore, conflicts, disputes, and arbitration between construction parties caused by poor construction management greatly lower the construction productivity on site. On the contrary, proper construction management can reduce potential risks when implementing investment and construction projects and make necessary conditions for timely and high-quality delivery of projects within the planned budget. Construction management is a professional service that pro-

vides a project's owner(s) with effective management of the project's schedule, cost, quality, safety, scope, and function [5], it plays an increasingly important role in various construction projects.

With the rise of the Industry 4.0 [6], the rapid development of information technologies (ITs) has greatly promoted and improved the construction industry. As a result, the terms Construction 4.0 and Intelligent Construction came into being. Construction 4.0 is a concept that proposed with reference to Industry 4.0, the definition of Construction 4.0 is dynamically evolving, for example, Sawhney et al. [7] defined Construction 4.0 as a framework that is a confluence and convergence of three broad themes: industrial production, cyber-physical systems, digital and computing technologies; Wu et al. [8] regarded Construction 4.0 as the integration of information and automation technologies in construction projects. There are many advanced technologies involved in Construction 4.0, and Forcael et al. [9] concluded four essential technologies to understand Construction 4.0 at present time: 3D printing, big data, virtual reality (VR), and Internet of Things (IoT). Except for advanced technologies, Construction 4.0 also brought advanced managerial approaches, García de Soto et al. [10] indicated that Construction 4.0 pushes construction organization and roles to be transformed in many aspects. The evolution from digitalization to intelligence is the mainstream of the development of Industry 4.0 [11]. As a derivative of Industry 4.0, the development direction of Construction 4.0 is the same so Intelligent Construction is the ultimate goal of Construction 4.0. Comprehensive development of Intelligent Construction requires intelligence in every segment, among which Intelligent Construction Management (ICM) takes an essential and inevitable part, it is the foundation of Construction 4.0 and Intelligent Construction. ICM is the intelligent pattern of construction management, it is a comprehensive evolution of traditional construction management in management concept, working mode and supporting measures which is achieved by the introduction of intelligent ITs and congenial managerial approaches.

Maturity is the competency, capability and level of sophistication of a selected domain based on a comprehensive set of criteria [12]. The ICM maturity of a certain construction enterprise is its ability to conduct ICM, it should be considered comprehensively from the technological perspective and from the managerial perspective. Therefore, the maturity assessment of ICM is the comprehensive consideration of the development condition of ITs and the application condition of managerial approaches. The purpose of maturity assessment is to identify a gap which can then be closed by subsequent improvement actions [13]. Many construction enterprises have been developing ICM and the fierce competition among them requires more efficient improvement plans for their ICM maturities. But only when the ICM maturity is accurately assessed can an enterprise select ITs and managerial approaches it needs to improve rather than extensively and aimlessly involving all kinds of intelligent ITs and managerial approaches, leading to a waste of human, material and financial resources. Therefore, the maturity assessment of ICM is of great significance for construction enterprises to find out shortcomings and formulate future improvement plans thereafter.

However, there is still a lack of effective systems, methods or even indicators to systematically assess the maturity of ICM which has encumbered the development of the construction industry. Existing studies and explorations towards ICM just focused on the innovation or application of one or several types of IT. Due to the differences between construction enterprises or projects, as well as the diversity and complexity of advanced ITs, the application depth and breadth of relevant ITs are different, their values and benefits remain uncertain. At the same time, the introduction of advanced ITs often leads to the change of managerial approach including organizational form and workflow. The mismatch between managerial approach and IT may also greatly limit the efficiency and value of ICM. Therefore, it is difficult to effectively assess the ICM maturities between different construction enterprises and discover their potential problems at the same time. In contrast, available maturity assessment models are increasingly being applied in other

informational, digital or intelligent fields as approaches for continuous process improvement [14], such as the Building Information Modeling (BIM) capability maturity model [15] and the digital maturity model [16]. These maturity models enable relevant organizations to clearly understand their development maturity and to make appropriate developing plans later.

In view of the above problems, this paper formulates a maturity assessment system for ICM. An intelligent maturity scoring table is established for the quantitative maturity assessment of ICM. The scoring table consists of five assessment dimensions and twenty assessment indicators. To present the assessment results in both overall and specific aspects, the levels of ICM maturity are set and the radar chart of assessment dimensions are designed. Finally, a case study of the assessments of two construction enterprises is conducted to validate the usage of the proposed assessment system and intelligent maturity improvement strategies are discussed. The assessment system can be used for leaders in construction enterprises to assess their ICM maturities and obtain vivid assessment results as well as improvement plans. For every construction enterprise, the scoring table transforms its ICM maturity into a score, corresponding maturity level plots the position of its ICM maturity in the whole industry, the radar chart of dimensions visualizes its strengths and weaknesses in dimensions, and finally the improvement strategies guide it to improve its ICM maturity according to the assessment results.

The rest of this paper is organized as follows. Section 2 reviews and summarizes previous studies related to ICM and mature assessment systems in other fields. Section 3 introduces the methodology of this research to formulate the maturity assessment system. Section 4 verifies the rationality and effectiveness of the proposed maturity assessment system through expert discussion. Section 5 enumerates the components of this maturity assessment system. Section 6 conducts a case study to validate the usage of the proposed assessment systems and discusses the methods to improve ICM maturity. Finally, section 7 summarizes the main contributions, limitations and future improvements of this research.

2. Literature review

In this section, studies concerning ICM are reviewed, and so as the investigations about assessment systems including methods and models in other informational, digital or intelligent fields to show mature examples.

2.1. ICM

Wu et al. [8] emphasized that Construction 4.0 heavily relies on data to build and maintain the interaction between the physical and virtual world. Because Intelligent Construction is the ultimate goal of Construction 4.0, data is also essential for ICM [17]. Intelligent ITs for data collection, transmission, aggregation, analysis and sharing can contribute to ICM [18], so can advanced managerial approaches supporting the data-oriented work mode, such as corresponding working post setting and personnel training, online personnel management and workflow interaction, etc. Therefore, the essence of ICM can be concluded as the review and feedback of various types of relevant construction information and data, which includes the collection, transmission and statistics of them, with the support of visualization, intelligent analysis and other technical means in this process.

A number of researchers investigated the attributes and development direction of ICM from the perspectives of intelligent ITs and advanced managerial approaches respectively. Aiming at intelligent ITs, Sawhney et al. [7] illustrated representative ITs that are used in Construction 4.0: BIM, cloud-based project management, augmented reality (AR)/VR, Artificial Intelligence (AI), cybersecurity, big data and analytics, block chain, laser scanner, IoT, etc. These ITs can also be applied to ICM. Aiming at managerial approaches, Woo et al. [19] reviewed different construction management methods by analyzing the efficiency of various methods currently applied to public construction projects.

They concluded that the direct supervision method is the most efficient construction management method because of lower cost and less time. García de Soto et al. [10] analyzed the transformation of construction organization and roles in Construction 4.0. Existing roles will evolve, and new roles will be created, for example, more employees with digital skills are needed. Many kinds of traditional construction work will be automated with the application of robotic systems. Furthermore, current fragmented projects will evolve to project-based integrations and eventually to a platform-based integration.

Besides, there are other studies that respectively focused on the application of just one certain IT or managerial approach towards ICM. In this study, we review and conclude nearly all the existing ITs or managerial approaches from literatures. Furthermore, we also discuss with experts in the construction industry to supplement novel ITs or managerial approaches which have not been published yet. All ITs or managerial approaches searched are concluded in Table 1, their effects on ICM and sources are also listed.

Table 1. ITs or managerial approaches supporting ICM.

Effect on ICM	IT or managerial approach	Source
Management platform	Platform with terminals for Personal Computer (PC), mobile and website	[20,21]
	Use a firewall and virus scan against intrusion	[22]
	AI voice assistant	[23]
	Application of 5G technology	[24]
Personnel management	Intelligent attendance system	[25]
	Human resource training and assessment	[26,27]
	Manage personnel information and user permissions in platform	[28]
	Monitoring of personnel health and performance	[29,30]
	Warning of overdue personnel age and qualification	Expert Discussion
	Incorporate COVID-19 guidelines into site health policies	[31]
Visualization	Establish BIM or Digital Twin (DT) in platform	[20]
	Construction simulation in multidimensional BIM environment	[32]
	Construction information sharing in platform	[33]
	Application of VR, AR and Mixed Reality (MR)	[34,35]
	Information carrier and displayer on site	[36]
Workflow	Submit and receive information through the platform	[37]
	Fill in and modify documents together in the platform	[38]
	Task management through the platform	[36]
	High-performance communication facilities on site	[39]
Production	Machinery operation and work tracking and monitoring	[40,41]
	Materials management using emerging technologies	[42]
Environmental impact	Waste and pollutant monitoring on site	[43,44]
	Site workplace environmental situation monitoring	[45]
Quality control	Automated data acquisition technologies on site	[46]
	Application of robots	[47]
	Mark locations of quality problems in models	[36]
	Declared quality problems tracking	[48]
	Vision-based inspection and real-time quality assessment	[49,50]
	Application of personal mobile devices	[51]

Table 1. *Cont.*

Effect on ICM	IT or managerial approach	Source
Schedule & Contract	Real-time schedule, contract and payment tracking and monitoring	[52,53]
	Warning of overdue schedule and contract	[54]
Time & Cost	Optimization of time and cost using learning curve	[55]
Information management	Record of engineering data and personnel operation	[56]
	Information decentralization, forgery and alteration prevention	[57]
	Intelligent search engine	[58]
	Data integration and simplification	[59]
	Application of information extraction (IE)	[60]
Work safety	Real-time video surveillance on site	[61,62]
	Worker safety device makes warning in proximity to certain areas	[63]
	Warning of unsafe behavior by real-time smart video surveillance	[61,62]
	Equipment collision prevention	[64]
	Warning of real-time fire, smoke, etc. on site	[65]
	Warning of abnormal value in data collected	[66]
Construction coordination	Dispatch list by intelligent Work Breakdown Structure (WBS) calculation	Expert Discussion
	Time-space conflicts management	[67]
Risk prevention	Make preventive measures with the use of prediction model	[68]

While all existing studies render positive influences on ICM individually, their research directions in general are too scattered to establish sufficient cooperation and connection with each other. Specifically, they suffer from several shortcomings — they:

- neglect the combined effect of IT and managerial approach;
- do not summarize all ITs and managerial approaches available for ICM;
- lack of methods to assess the application maturities of ITs and managerial approaches in ICM; and
- lack of practical and appropriate plans to improve the ICM maturity of construction enterprises.

In this study, existing intelligent ITs and advanced managerial approaches available for ICM have been reviewed, the combined effect of ITs and managerial approaches is considered. Therefore, the assessment system can be established by extracting assessment objects from these contents, and then maturity improvement plans are provided.

2.2. Assessment systems in other fields

This study reviews some representative maturity assessment systems in other informational, digital or intelligent fields, as listed in Table 2. Berghaus and Back [69] indicated that a maturity assessment model should consist of dimensions and criteria, which describe the areas of action, and maturity stages that indicate the evolution path towards maturity. Though these assessment systems have different assessment targets using different assessment methods, they all set assessment dimensions and criteria, as well as corresponding development guide to improve maturity. Furthermore, [15] and [70] set maturity levels to present the overall assessment results, and [70] designed a radar chart of dimensions to present the to visualize the strengths and weaknesses in each dimension. The assessment method, advantage and priority of each assessment system can offer important reference to the assessment methods needed in this research: (1) Scoring on dimensions is a quantitative assessment method which has been proved popular and easy

to use. (2) Dimension(s) to assess the management capacity should be set, including organizational framework, personnel management, workflow, etc. (3) Assessment results should be displayed clearly from both the overall and specific perspectives. For example, maturity levels and radar chart of dimensions can be applied respectively for the overall and specific perspective.

Table 2. Maturity assessment systems in other informational, digital or intelligent fields.

Research	Assessment target	Assessment method	Dimension	Advantage and priority
[71,72]	BIM adoption across markets	Score on dimensions	5	Comprehensive consideration of policies, management and technologies
[15]	BIM capability maturity	Score on dimensions	11	Needed dimensions can be selected from the given 11 dimensions
[16]	Digital maturity for companies	Single choice questions	2	Rapid assessment process
[73]	Digital readiness maturity for manufacturing	Yes no questions	5	High objectivity
[74]	Project complexity	Analyze from dimensions	5	Detailed assessment results
[75]	Digital maturity of construction projects	Score on dimensions	4	Introduction of the frequency of assessment objects
[70]	Digital maturity on construction site	Score on dimensions	11	Comprehensive assessment objects

3. Methodology

In this study, assessment indicators are set with criteria from different dimensions. Steps to develop the assessment system are listed below, as shown in Figure 1.

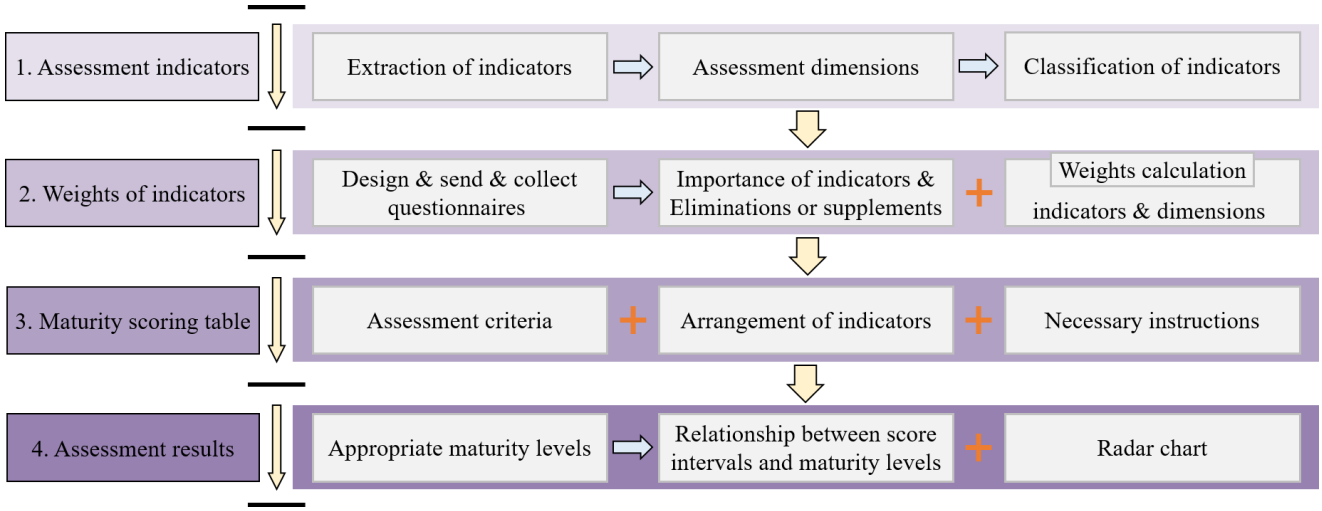

Figure 1. The construction process of the assessment system.

The first step is the determination of assessment indicators. In the whole assessment system, the maturity scoring table is the most important part whose basic elements are assessment indicators. There are a large number of assessment indicators extracted, so it is necessary to set up assessment dimensions and reasonably classify all indicators to facilitate the viewing and use of them, and also help construction enterprises to assess their own ICM maturity from the perspective of each dimension.

The second step is the calculation of the weights of assessment indicators. This study uses questionnaires designed in correspondence to the Precedence Chart Method (PCM) [76,77] to consult experts on each indicator's importance to the maturity assessment of ICM, then the weight of each assessment indicator and dimension can be calculated with the results of questionnaires. Scores of the assessment indicators and dimensions in the maturity scoring table can later be calculated by converting their weights.

The third step is the design of the maturity scoring table. The indicators cannot be used directly so that assessment criteria should be set to instruct assessors when scoring. Arranging each indicator according to its dimension and then adding corresponding score and assessment criterion make a complete maturity scoring table, necessary instructions for each content should also be written to guide assessors to use it correctly.

The last step is the analysis of assessment results. The presentation of assessment results should take into account overall and specific aspects. This research uses maturity levels to plot the position of the ICM maturity in the whole industry and a radar chart [78] of dimensions to visualize the strengths and weaknesses in each dimension. Therefore, this step includes the setting of appropriate maturity levels and corresponding relationship between score intervals and maturity levels, as well as the design of the radar chart.

3.1. Determination of the assessment indicators

A complete assessment indicator includes assessment object, weight and criterion. The scope of construction management is confined but intelligent ITs and advanced managerial approaches supporting ICM over the scope at present are unlimited and uncountable, not to mention new ones being developed. The responsibility of indicators is to screen objects and contents that can best reflect the development of ICM. Therefore, assessment indicators in this study do not list and conclude ITs and managerial approaches available for the scope, but abstract attributes that reflect the development situation of these ITs and managerial approaches instead. In a word, it's not detailed ITs and managerial approaches enterprises use but attributes enterprises satisfy that develop ICM.

3.1.1. Extraction of assessment indicators

The extraction of assessment indicators needs to comprehensively contain factors from the following three aspects.

(1) Construction management scope, to determine the assessment scope of indicators. According to regulations and requirements of the construction industry, aspects and fields that the construction management should be responsible for are clarified, which should be covered by assessment indicators.
(2) ITs and managerial approaches supporting ICM, to abstract attributes as assessment objects. Comprehension on the application status of relevant ITs and managerial approaches can fully tap the application potential and highest maturity of each one, that is, the scale of attributes.
(3) Existing assessment methods and systems, to refer to successful experiences. As mentioned, there are already advanced maturity assessment methods and systems in other fields, as shown in Table 2. Among them are successful experience in indicator extraction, assessment dimension setting and assessment methods.

The above factors are extracted from both literatures and expert discussions. Referring to literatures can obtain a comprehensive grasp of the relevant contents, discussing with experts can make a supplement, such as details omitted in literatures, latest management technologies which are not published yet, and matters require attention for acquired contents in practical application. These factors should be considered together during collection. First, find out ITs and managerial approaches that can be applied in fields according to the management scope, as shown in Table 1. Then search for application status of relevant ITs and managerial approaches to conclude abstract attributes of them which are regarded as preliminary assessment objects. Finally, with reference to the framework of other maturity assessment systems, establish indicators by adjusting and reorganizing

preliminary assessment objects according to service objects of all ITs and managerial approaches. Make sure that complete independence of indicators is obtained and there is no overlap between them. The indicator extraction process is shown in Figure 2. In a word, the assessment indicators are extracted from literatures and expert discussions through these three procedures, each indicator does not have direct sources of literature or expert discussion because of these fused procedures.

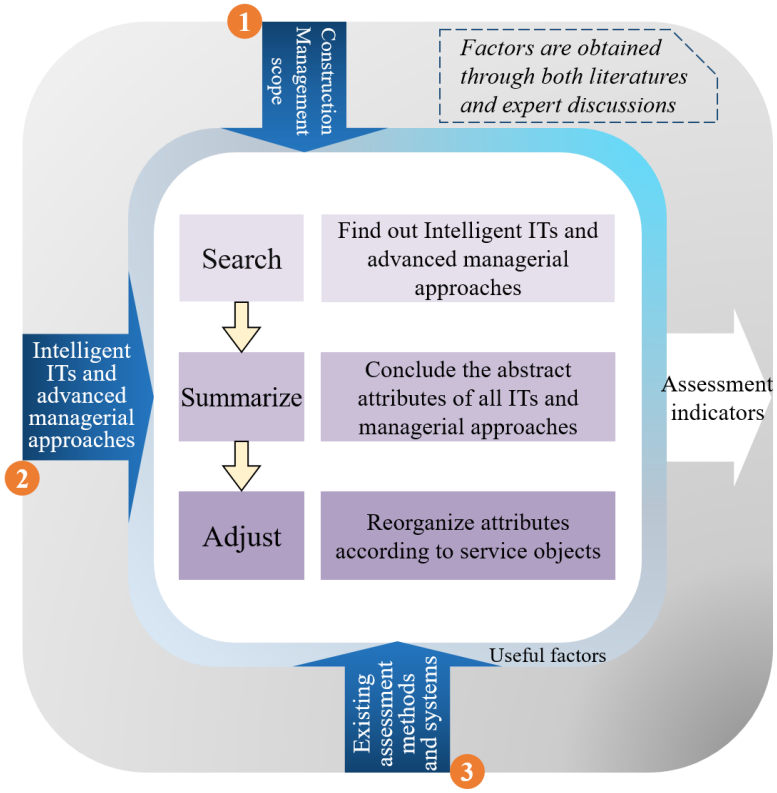

Figure 2. The indicator extraction process.

3.1.2. Setting of assessment dimension and indicator classification

It is indicated by the literature review that a dimension to assess the management capacity should be set. Among all indicators, there are some that describe the personnel organization and management or workflow of construction management, so first set a dimension for them. The remaining indicators describe ITs and managerial approaches related to the construction management itself. Blanco et al. [79] illustrated many specific and clear activities to differentiate technologies used during different construction phases, including the phases of design, preconstruction, construction and operations. These specific activities classified ITs and managerial approaches for construction management properly, but they are too scattered. According to the essence of ICM, dimensions for remaining indicators can be set by composing these specific activities (definitions of these specific activities can be seen in [79]). Considering the service objects and application fields of the remaining indicators, set four dimensions for them, each dimension and its components are shown in Table 3. On the whole, five assessment dimensions are set following strict internal logic to ensure that there is no overlap between each other, the meaning and description of each assessment dimension are shown in Table 4.

In order to make each indicator more consistent with the meaning and description of corresponding dimension when classifying, indicators should be adjusted appropriately after the determination of dimensions, so that each indicator can be clearly and uniquely

classified into a certain dimension, and the number of indicators contained in each dimension should be as close as possible. After the determination of dimensions and the adjustment of indicators, available indicators can be classified into each dimension.

Table 3. Assessment dimensions and their components for ITs and managerial approaches.

Assessment dimension	Activities in [79]
Information collection and monitoring	Materials management, Equipment management
Information transmission and aggregation	Field Productivity, Performance dashboard
Decision-making supported by visualization	Digital design, Design management, Contract management, Document management
Intelligent analysis and deduction	Estimating, Construction relationship management, Market intelligence, Quality control, Safety

Table 4. Meaning and description of each assessment dimension.

Assessment dimension	Meaning and description
I. Organizational framework and working process	More suitable organizational framework, more powerful personnel management and more efficient work mode required by ICM.
II. Information collection and monitoring	Collection and monitoring of various types of construction information and data through collection and measurement equipment arranged on construction site.
III. Information transmission and aggregation	Transmission and aggregation of information and data collected on site within time limit, proper storage and archiving to prevent loss and tampering.
IV. Decision-making supported by visualization	Visualization and modelling of engineering information and simulation of construction operation to support decision-making.
V. Intelligent analysis and deduction	Analyze engineering information with the application of intelligent technologies to provide calculation, detection, prediction, and optimization, etc.

3.2. Calculation of the weights of assessment indicators

The questionnaire in this study mainly investigates respondents from three aspects: (1) Basic information of respondents, including professional field and title, working post and year, to show the objectivity of the questionnaire. (2) Eliminations or supplements for existing indicators and judgement of the suitability on the setting of assessment dimensions and on the classification of each assessment indicator, to ensure the rationality of assessment dimensions and indicators. (3) The consultation of respondents about the importance of each indicator to assess the maturity of ICM. The questionnaire is designed following the PCM, seven-point Likert scale [80] is used for respondents to make a choice from very low to very high on the importance of each assessment indicator, where each choice corresponds to a point from 1 to 7, as shown in Figure 3.

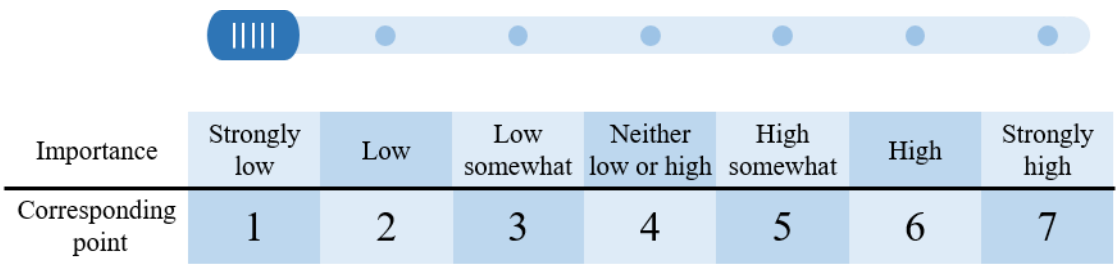

Figure 3. The seven-point Likert scale.

The PCM uses a comparison matrix to calculate the weights of target objects, as shown in Table 5, the left columns in the table refer to the comparing objects, while the upper rows are the compared objects. In this study, the respondents' opinions on the importance of each assessment indicator is converted into a point from 1 to 7 by the seven-point Likert scale. Suppose that there are n indicators for comparison and their average points of all respondents are calculated, it is easy to know that the indicator with higher point possesses higher importance. Choose I_1 and I_4 as an example for a pairwise comparison: if I_1 is more important, then $a_{14} = 1$ and $a_{41} = 0$; if I_4 is more important, then $a_{14} = 0$ and $a_{41} = 1$; if I_1 and I_4 are equally important, then $a_{14} = a_{41} = 0.5$. Finally, the weight of each indicator can be calculated:

$$w_i = \frac{s_i}{\sum_{i=1}^{n} s_i}$$

In this function, w_i is the weight of the indicator i, s_i is the sum of all elements in the row i.

Table 5. Comparison matrix of PCM.

Comparison Indicator	I_1	I_2	I_3	I_4	…	I_n	Sum
I_1	$a_{11} = 0.5$	a_{12}	a_{13}	a_{14}		a_{1n}	$s_1 = \sum_{i=1}^{n} a_{1i}$
I_2		0.5					
I_3			0.5				
I_4	a_{41}			0.5			
…					0.5		
I_n						0.5	

3.3. Design of the scoring table

The assessment indicator itself is the summary of ITs and managerial approaches that construction enterprise uses and it does not contain the description of the highest intelligent maturity of each IT and managerial approach. Setting assessment criteria for each indicator is essential for assessors to make more accurate judgments when scoring each assessment indicator. After that, assessment indicators with scores and assessment criteria can be reasonably arranged according to their dimensions. Finally, the complete scoring table is finished when necessary instructions for each content are written for correct use.

3.4. Analysis of assessment results

The scores obtained by assessors on the assessment of construction enterprises using the scoring table represent their ICM maturities. The score can indeed intuitively reflect the overall ICM maturity of each construction enterprise, however, as each enterprise commonly only knows its own score, it cannot plot the position of itself in the whole industry without comparison with other enterprises. Besides, its strengths and weaknesses between different assessment dimensions remain unclarified.

In this study, scores are converted into corresponding maturity levels as the overall presentation of assessment results. The division of maturity levels must ensure that enterprises at the same level possess ICM maturities at roughly the same standard. How many maturity levels should be set? Whether the score intervals between levels should be consistent? How to allocate them if they are inconsistent? These questions can be answered only when preset maturity levels and the corresponding relationship between score intervals and maturity levels are further verified and corrected. Verification and correction of mentioned contents are also realized through expert discussion, so for convenience, they are arranged to be discussed together in the verification section. Also, in order to clarify

the strengths and weaknesses of enterprises in assessment dimensions, the radar chart of dimensions is designed as the specific presentation of assessment results.

4. Verification of the assessment system

Till now, determined contents are obtained mainly by theoretical analysis so crucial attributes of this assessment system have not been verified through application. Wernicke et al. [70] developed a framework for assessing digital maturity of construction site operations. To examine and verify the framework, they conducted a case study on one construction site. The digital maturity of that site was firstly calculated by the proposed framework. Then they discussed with the assessor about the detailed status of the digitalization of that site as well as the strengths and weaknesses. The consistency between the assessment results and the discussion results verified the proposed framework. Furthermore, the usability and benefits of this framework were also discussed. In this research, we also use expert discussion to verify our proposed assessment system. However, rather than conduct just one discussion with one assessment target, we conducted two rounds of expert discussions with experts from several construction enterprises. The first round was conducted to verify the scoring table and preset the maturity levels. The second round was conducted to verify those preset maturity levels. The overall verification process is shown in Figure 4. Besides, more details are discussed in our expert discussions.

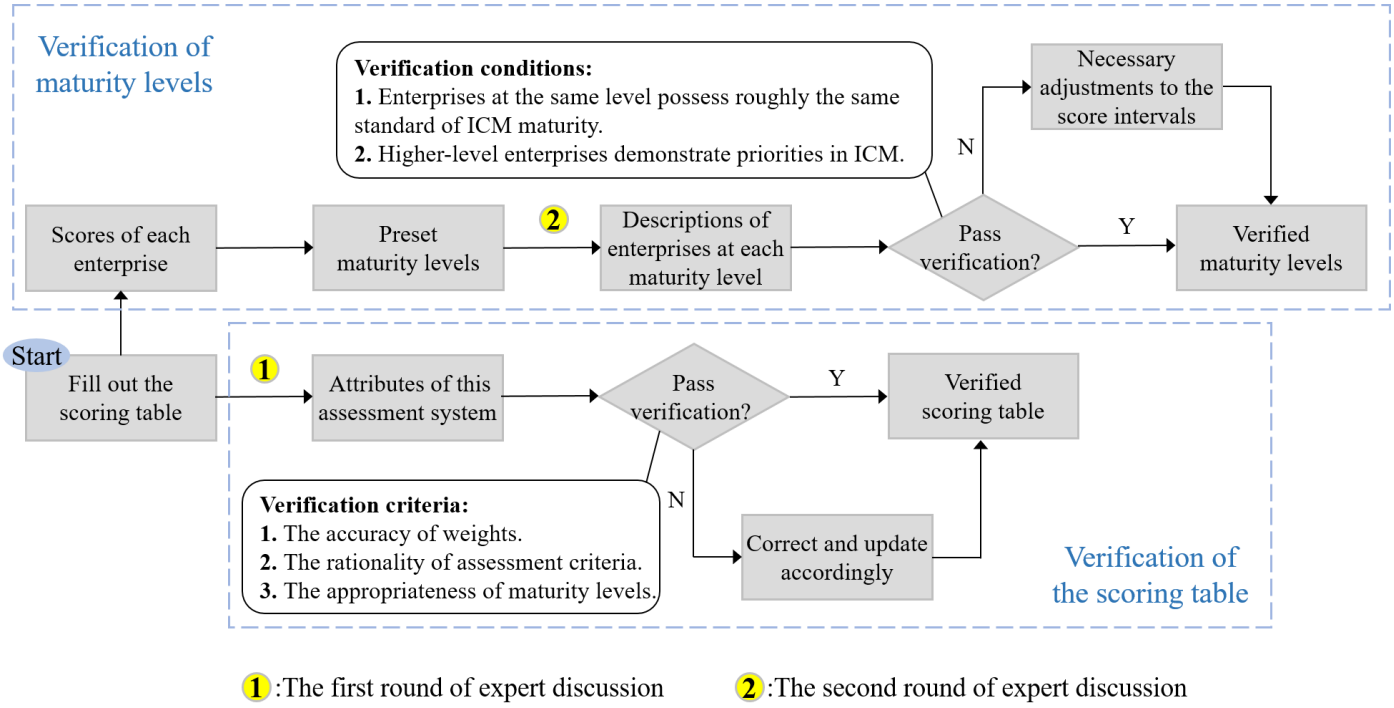

Figure 4. The overall verification process.

4.1. Verification of the scoring table

The scoring table was sent to leaders of many construction enterprises and then they filled out the scoring table according to ICM maturities of their own enterprises. Except for collecting the scores of each enterprise, we discussed with their leaders about the crucial attributes of this assessment system. Through the feedback of these leaders, related contents of the scoring table can be verified and updated.

4.2. Verification of maturity levels

After the collection of the scores of each enterprise, the distribution of all scores were obtained. Rough score intervals can be divided by clustering all the scores and thus the

maturity levels can be preset. According to the score intervals of the preset maturity levels, participated enterprises were differentiated into different maturity levels. Through detailed discussions with leaders from several representative enterprises at each maturity level, summary descriptions of the overall ICM maturity of enterprises at each maturity level were formed. The setting of maturity levels must satisfy two criteria: (1) enterprises at the same level possess roughly the same standard of ICM maturity; (2) enterprises at higher levels demonstrate relatively obvious priorities in ICM maturity compared to those who have lower levels. Necessary adjustments to the set score intervals were conducted to satisfy the two principles and the appropriate corresponding relationship between maturity levels and the scoring results can be finally obtained. So far, all contents in the whole assessment system have been verified to ensure their accuracy, rationality and appropriateness.

5. Assessment system

5.1. Assessment indicators and dimensions

To obtain more extensive responses, we set two criteria for selecting the potential respondents for the questionnaire: (1) respondents with ample work experience in construction management or with ample knowledge of intelligent technologies; (2) respondents from as many as possible professional fields. Leaders from many different construction enterprises feel interested in our study, so they helped us select employees from their enterprises according to these two criteria to answer the questionnaires. They tell us that older employees tend to have more work experience while younger employees tend to have more knowledge about intelligent technologies. We offer them a QR code which can be scanned to reach our questionnaire and these leaders assign qualified employees to fulfill the questionnaire. The questionnaires were collected two weeks after sending the QR code to leaders, incomplete ones were deleted and finally there were 706 questionnaires considered valid. Basic information of respondents is shown in Table 6. Respondents think that existing indicators are proper so there is no need for eliminations and supplements. Furthermore, respondents provide us with suggestions on setting the assessment criteria, such as taking the operability of ITs into account.

Table 6. Basic information of respondents.

Professional field	Amount	Professional title	Amount	Working post	Amount	Working year	Amount
Roads and bridges	483	Primary	131	General supervisor	166	Within 5	73
Tunnels	60	Middle	337	Specific supervisor	346	5-10	140
Traffic engineering	84	Vice-senior	170	Supervisor	148	10-20	301
Electro mechanics	10	Senior	68	Enterprise administrator	32	More than 20	192
Others[1]	69			Others[2]	14		

[1] Safety, Structure, Electric power, Water transport, Contract, Experiment and Engineering economy.
[1] Vice general supervisor, Consultant and Experimentalist.

There are twenty indicators in total and their accurate weights can be calculated using PCM. However, in order to make the data neat and easy to use, it is necessary to make adjustments within an appropriate range and finally keep the outcome in integer. Scores of the all assessment indicators and dimensions in the maturity scoring table are calculated by converting their weights, as shown in Table 7, they illustrate not only the present situation but also the future development trend of ICM.

(1) The first dimension has the highest weight of nearly 40 percent in the whole scoring table. It describes the personnel organization, management and workflow of ICM. Effective personnel organization and management are crucial basis for every kind of enterprise and company to maintain competence and it is the same for construction

enterprises. Furthermore, as ICM is still rapidly developing, more and more suitable workflow will always be a necessary key for construction management to develop more intelligent and for ITs and managerial approaches to maximize their superiorities. According to the expert discussion, nearly every enterprise has developed their own cloud platform. They work online and their organizational framework was adjusted to adapt to the intelligent working mode.

(2) Indicators I-5, I-6, III-3, I-1and V-2 have the top five highest weights. According to the expert discussion, they are all present developing focuses for ICM. Most enterprises have been collaborating with researchers from institutes and universities to develop ITs and managerial approaches these indicators describe. These ITs and managerial approaches have been realized to varying degrees among different enterprises. Due to the high weights these indicators possess, they are now decisive factors for a construction enterprise's ICM maturity.

(3) Indicators IV-3, V-3 and V-1 have relatively low weights. According to the expert discussion, only a few employees have contacted with ITs and managerial approaches these indicators describe and the development levels of these ITs and managerial approaches among different enterprises are pretty low. Besides, publications about these ITs and managerial approaches are mostly limited to theoretical or prospective, they have not been applied to ICM comprehensively and maturely. However, as the publications imply, these ITs and managerial approaches have great benefit and considerable application potential to ICM, including VR [34], AR [35], prediction model [68], time-space conflicts management [67], etc. A number of construction enterprises have included these ITs and managerial approaches in their future development plans and their weights will definitely increase in the future.

Table 7. Weights of dimensions and indicators.

Assessment dimension	Assessment indicator
I. Organizational framework and working process (38)	1. Working post setting (8), 2. Collaboration mode (7), 3. Personnel training (4), 4. Personnel assessment (1), 5. Workflow (9), 6. Transaction tracking (9)
II. Information collection and monitoring (12)	1. Collection range (6), 2. Collection frequency (3), 3. Equipment integration (3)
III. Information transmission and aggregation (22)	1. Transmission speed (6), 2. Information integration (7), 3. Information storage (9)
IV. Decision-making supported by visualization (12)	1. Data visualization (2), 2. Knowledge base management (4), 3. Expanding reality (1), 4. Comprehensive decision (5)
V. Intelligent analysis and deduction (16)	1. Auxiliary calculation (2), 2. Anomaly Identification (8), 3. Deduction and prediction (1), 4. Early warning and optimization (5)

5.2. Maturity scoring table

The scoring table is attached in the appendix, assessment criteria for each indicator are set according to the application status of relevant ITs and managerial approaches.

5.3. Maturity levels

Maturity levels and corresponding score intervals are set according to the two criteria, as shown in Table 8. Five maturity levels are set among which there is a particular level called "Minimum Intelligent Maturity". During expert discussions, we found that ITs and managerial approaches described by many indicators have been well developed. Therefore, more than half of the scores in the scoring table are easily acquired by every construction enterprise. Enterprises with scores less than 60 must demonstrate shortcomings

in so many aspects under this circumstance. Therefore, the lowest maturity level "Minimum Intelligent Maturity" is set to conclude these enterprises which are not "intelligent" enough. As mentioned, many leaders of different construction enterprises filled out the scoring table and their scores were collected. The number of enterprises at level 2 is the largest. Few enterprises locate at the Minimum Intelligent Maturity and a small part of enterprises just entered level 3. There is not even one enterprise that entered level 4.

Table 8. Maturity levels and corresponding score intervals.

Maturity level	Score interval
Minimum Intelligent Maturity	< 60
1	[60,70)
2	[70,80)
3	[80,90)
4	[90,100]

5.4. Radar chart

The radar chart is designed to compare the relative development of each dimension, but the weights of each dimension are different so that their full scores in the scoring table are also different. When using the radar chart, scores of each dimension in the scoring table should be converted into a centesimal system:

$$R_i = \frac{T_i}{W_i} \times 100$$

In this function, R_i is the score of the dimension i in the radar chart, T_i is the score of the dimension i in the scoring table and W_i is the weight of dimension i (shown in Table 7). Then the pentagon representing the ICM maturity of the enterprise in dimensions can be drawn.

6. Case study

The proposed assessment system was examined in a case study of two construction enterprises A and B. These two enterprises are both located in Hangzhou, a city in south China. Enterprise A mainly focuses on the construction of highways and canals, enterprise B mainly focuses on the construction of highways and railways. One leader from each of the two enterprises filled out the maturity scoring table according to the actual situations of their enterprises.

6.1. Assessment results

Their assessment results using the maturity scoring table were 78 and 81 respectively. Therefore, the ICM maturities of enterprise A and B were very close, they both almost entirely satisfied the demands of level 2 and enterprise B has just entered level 3. Furthermore, to show their strengths and weaknesses in each dimension, a radar chart of their ICM maturities is drawn, as shown in Figure 5.

Then two discussions with these two leaders were conducted respectively for detailed situations of their ICM maturities, as shown in Table 9. Enterprise A and B have paid great attention to the development of ICM and they have made specific development plans for the introduction and application of several ITs and managerial approaches. However, their unsystematic development plans have caused different kinds of deficiencies in each dimension, and then led to relatively elementary maturity levels thereafter. Enterprise A and B are located in the same city and they have know each other for years. They both commented that their development situations of ICM are very close and they admitted that their maturity levels are relatively elementary. Not enough new roles have been set in enterprise A and existing roles have not been thoroughly adaptive to ICM,

leading to a burden to the newly developed workflow. It is the main reason, according to our assessment system, for enterprise A to have a slight gap in scores compared to enterprise B.

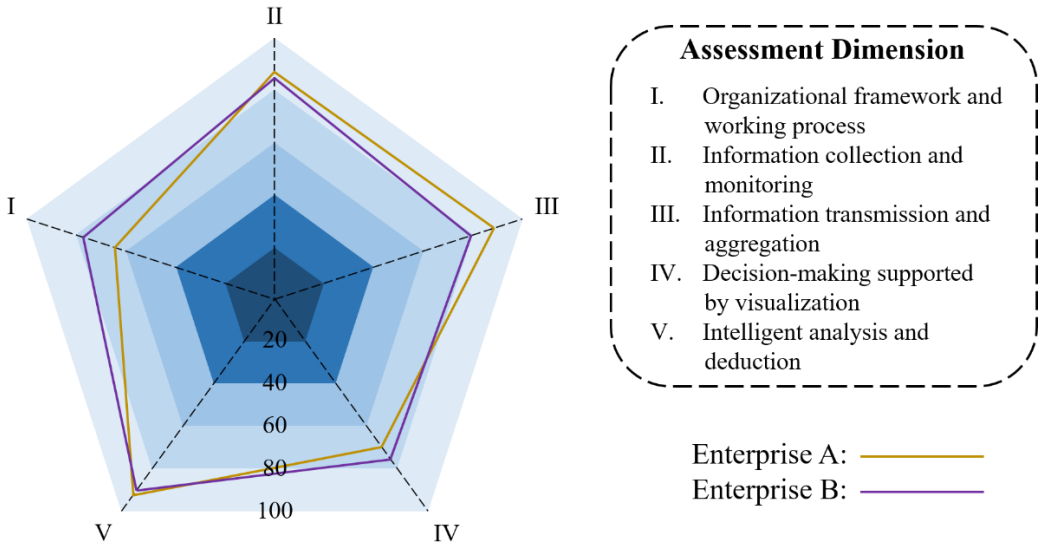

Figure 5. The radar chart of enterprises A and B.

Table 9. Detailed situations of the ICM maturities of enterprise A and B.

Assessment dimension	Strength	Weakness
I. Organizational framework and working process	A & B: Develop a construction management platform, transactions are strictly tracked. A: Personnel assessment monthly. B: Many new roles are set.	A & B: Insufficient personnel training, some employees are still not skilled with the platform, workflows are still not clear. A: Only a few new roles are set.
II. Information collection and monitoring	A & B: Many data collection devices are arranged on construction site. A: Enough mobile phones for management. B: A few attempts on equipment integration.	A: Almost no equipment integration, efficiency and accuracy of data collection are low.
III. Information transmission and aggregation	A & B: All data and information collected are stored. A: Efficient information aggregation (a new role was set for that).	A & B: Inadequate coverage of network signal on site, real-time upload and receipt cannot be guaranteed.
IV. Decision-making supported by visualization	A & B: Many kinds of important data and information are real-time displayed by adequate display devices.	A & B: Poor interaction between different kinds of models, no application of VR, AR or MR.
V. Intelligent analysis and deduction	A & B: Many intelligent functions and algorithms are developed. A: Employ a software system team.	A & B: The frequency of use is unstable.

6.2. Validation of the assessment system

Despite many existing weaknesses and deficiencies for these two construction enterprises, the biggest problem for them is the low capacities of organizational management which are caused by the incompletely adjusted working posts. Even if there are ITs and

managerial approaches developed, they cannot be efficiently applied. Therefore, we strongly recommend these two enterprises to set more new roles first. Then other measures can be applied, such as training employees more often, improving the network signal on site, introducing VR, AR or MR, etc. After the discussions, these two leaders claimed that they would adjust their development plans according to our recommendations.

In total, these two leaders spoke highly of the usability of the assessment system. They commented that the assessment criteria helped them to reach deeper into their actual development situation of ICM; and the assessment dimensions are essential for them to find their deficiencies and weaknesses in detail. Therefore, the case study proves the validation of the proposed assessment system, it can provide not only overall and specific representations of the ICM maturity of a certain enterprise, but also targeted development plans thereafter.

6.3. Discussion

There should also be a potential, anticipated or typical development path to the desired target state after evaluation [81]. The ultimate purpose of the maturity assessment of the ICM is to efficiently and accurately improve its maturity. After assessment using the maturity scoring table, construction enterprises can further understand details of their weaknesses through the indicators with lower scores, and these are the aspects that needs to improve most. To provide specific improvement plans for construction enterprises, this study discussed improvement strategies from two perspectives.

The first perspective is the detailed ITs and managerial approaches. This study extracts and summarizes ITs and managerial approaches that can improve the maturity of ICM during the extraction of the assessment indicators. They can be used to help construction enterprises that have been assessed to find out and fill the present gaps. These ITs and managerial approaches are listed in Table 1 where they are very detailed and specific. They are simply classified according to their effects on ICM and their sources are contained in the table, which can be searched and consulted by enterprises to understand the development and application methods of any ITs and managerial approaches in detail.

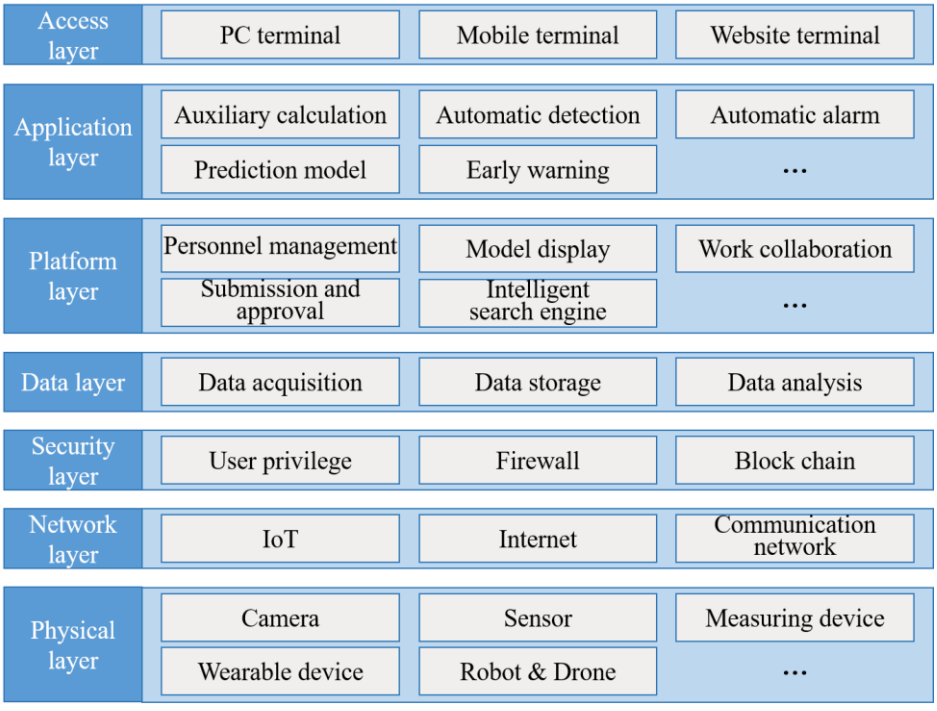

Figure 6. Framework of enterprises at level 4.

The second perspective is the framework of enterprises at level 4. Organizations engaged in information, digitalization, or intelligence have similar frameworks which include many layers. However, each layer in the framework of different kinds of organizations consists of different components. The frameworks of highly developed organizations are powerful and comprehensive where all layers have undergone extensive development. When a certain construction enterprise has the highest maturity of ICM, it must have the 4th maturity level and have developed almost every IT and managerial approach in Table 1. Under this circumstance, each layer in its framework possesses adequate components, representative components are summarized according to the sources of ITs and managerial approaches in Table 1, as shown in Figure 6. This framework can be used for reference by construction enterprises to supplement their own framework and finally continuously improve their ICM maturities.

In general, construction enterprises are able to obtain suitable improvement plans synthetically from these two perspectives after assessment, as shown in Figure 7.

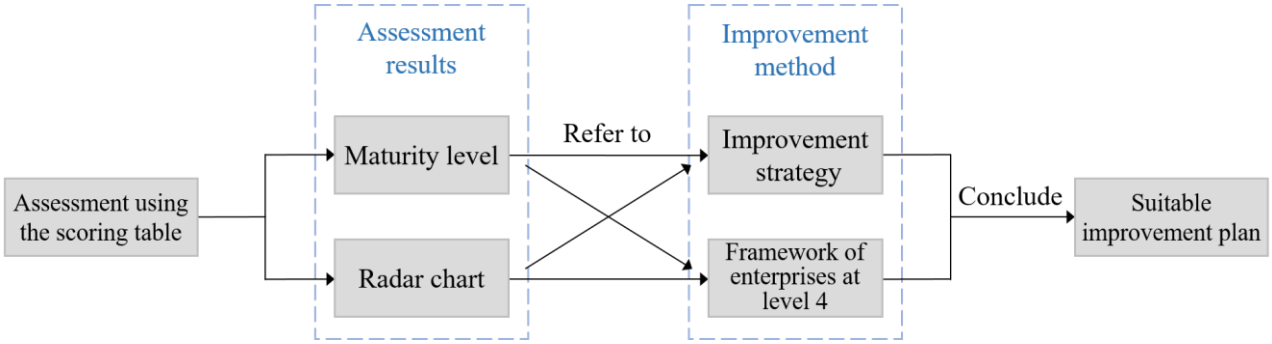

Figure 7. Method to obtain suitable improvement plans.

7. Conclusions

The ICM is rapidly developing at present but there is still a lack of systems, methods or even indicators to systematically assess the maturity of ICM. In this study, we develop a maturity assessment system through literature reviews, questionnaires, expert discussions and a case study. The maturity assessment system consists of a maturity scoring table, maturity levels and a radar chart of dimensions, which can be used by construction enterprises to assess their ICM maturities and formulate suitable future improvement plans thereafter. First, fill out the maturity scoring table based on the ICM development situation of a certain construction enterprise. Then the score can be converted into a maturity level and a dimension radar chart, the position of the enterprise in the whole construction industry and its own strengths and weaknesses can be accurately understood. Finally, the suitable improvement plan of this construction enterprise can be set up with reference to the improvement strategy and the framework of enterprises at level 4.

The maturity scoring table consists of five assessment dimensions and twenty assessment indicators. When using it, assessors need to score each indicator based on their subjective judgement on their own construction enterprises. Since the subjective difference is inevitable, it is strongly recommended that the ICM maturities of each enterprise are assessed by more than one leader and the average of their scores is taken as the final result. According to the scoring table, developing ITs and managerial approaches which support organizational framework and working process is of great significance for construction enterprises to reach high ICM maturity. Many enterprises do not pay enough attention to advanced managerial approaches because they have not realized the unimagined progress that these approaches can bring to them. During our discussion with leaders in construction enterprises, we found that many enterprises had already developed adequate ITs and managerial approaches. Unfortunately, a big number of ITs and managerial approaches remained unused or insufficiently used for the lack of suitable organizational

framework and working process, leading to a low ICM maturity with a huge amount of resource waste.

The study has two limitations. First, the study uses the maturity scoring table as the assessment method because of the high complexity in the assessment process of ICM maturity. Although the scoring table is accurate and reliable, it is not efficient enough. Future research can use the assessment indicators in this study to establish more efficient maturity assessment methods for ICM, such as the assessment methods consisting of yes no questions, flowcharts, or single choice questions. Second, the assessment indicators and their weights in this study represent the development situation of ICM at present and in the short-term future. There is still a long way for construction management to reach thoroughly intelligent since most construction enterprises are located at level 2 and there is nearly no one that has entered level 4. However, there will be a time when most enterprises have entered level 4 because of the efforts that the whole construction industry is making. Meanwhile, more ITs and managerial approaches will come into use and serve as indicators, the weights of all indicators must change with time going by. Future studies are recommended to add new indicators and correspondingly adjust the weights of all indicators. For example, the ITs and managerial approaches towards automated are developing rapidly and will occupy more and more weights [82,83].

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Appendix A

Table A1. The maturity scoring table for ICM.

Dimension	Indicator	Criterion	Score
I. Organizational framework and working process	1. Working post setting: Adjust former posts, set specific responsibilities and corresponding organizational relationships for all posts.	Reasonable, perfect personnel allocation and gross wage.	8
	2. Collaboration mode: Conduct online personnel management and workflow interaction based on the management platform.	Real-time upload, reminder and feedback.	7
	3. Personnel training: Train personnel in a variety of ways to adapt to the working mode of ICM.	Check regularly and trace the training data.	4
	4. Personnel assessment: Use a variety of data sources to assess the attendance and performance of personnel.	Quantitative, qualitative and objective assessment.	1
	5. Workflow: Assign designated responsible personnel to complete workflow of each task with clear work sequence.	Smooth work flow with high efficiency.	9
	6. Transaction tracking: Record and track the processing flow and relevant responsible personnel of all transactions.	Clearly record the process and responsible person.	9
II. Information collection and monitoring	1. Collection range: Collect as many types of data and information as possible on site and make the collection range as wide as possible.	Collect comprehensively, all key areas covered.	6
	2. Collection frequency: Collect data and information as frequently as possible to improve their continuity.	Avoid interruptions in data and information acquisition.	3
	3. Equipment integration: Develop equipment that collect multiple data and information simultaneously and efficiently.	Improve the accuracy of data and information collection.	3
III. Information transmission and aggregation	1. Transmission speed: Improve the transmission speed to ensure the timeliness of data and information transmission.	Ensure real-time uploading and receiving on site.	6
	2. Information integration: Integrate, fuse, summarize and transform the collected data and information.	Automatic preprocessing of data and information.	7
	3. Information storage: Archive and save the collected data and information to support efficient utilization and security management.	Store all data in the whole life cycle of the project.	9
IV. Decision-making supported by visualization	1. Data visualization: Model, visualize and simulate using all kinds of construction data and information.	Concrete, intuitive and accurate visualization.	2
	2. Knowledge base management: Upload construction data and information to the platform and set search function for viewing.	Comprehensive categories, accurate search results.	4
	3. Expanding reality: Assist scheduling and management with the help of VR, AR, MR and other extended reality technologies.	Widely used in the complete work flow.	1
	4. Comprehensive decision: Real-time display the data and information being monitored and collected.	Display on a variety of devices widely.	5
V. Intelligent analysis and deduction	1. Auxiliary calculation: Intelligently calculate the schedule, cost, etc. with collected data and information.	Introduce intelligent computing for all calculation processes.	2
	2. Anomaly identification: Identify occurring abnormal conditions including automatic detection of construction results and automatic alarm of unsafe behaviors, etc.	Comprehensive categories, fast detection and identification speed with high accuracy.	8
	3. Deduction and prediction: Establish a prediction model based on collected data and information to predict the work focus and potential risks in the next stage.	The model considers all types of data and information, real-time update.	1
	4. Early warning and optimization: Adjust the management plan according to the prediction results to avoid possible risks and improve the project management ability.	Real-time optimize the management plan and implement it on time.	5

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