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Building a Digital Transformation Maturity Evaluation Model for Construction Enterprises Based on the Analytic Hierarchy Process and Decision-Making Trial and Evaluation Laboratory Method

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Abstract: With digital transformation underway in various Chinese construction enterprises, each enterprise has progressed differently, and a clear direction for future digital transformation and upgrading is lacking. As such, the importance of measuring the level of digitization among Chinese construction enterprises is increasing. This paper presents a model for evaluating digital transformation maturity within construction enterprises. The model considers six aspects: digital strategy, digital business applications, digital technology capabilities, and so on. The digital maturity of enterprises is determined using the Analysis of Hierarchy (AHP)-Decision Making Experiment and Evaluation Laboratory (DEMATEL) method. Technical abbreviations are explained when first used. This study demonstrates that digital business applications are the most significant primary indicator, with a weight of 29.53%. The success of digital transformation in the construction industry is strongly influenced by the interconnection between digital technology and construction sites, as well as other factors such as new technical personnel, digital infrastructure, digital innovation, and innovation iteration ability. It is crucial to understand how digital technology and the construction industry can effectively connect in order to achieve success in this realm. This paper aims to enhance the digital transformation capabilities and efficiency of construction companies and boost their core competitiveness through targeted measures.

Keywords: construction enterprise; digital transformation maturity; AHP-DEMATEL

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1. Introduction

It is well known that the digital resources of enterprises have great potential for transformation and innovation, which can change their production methods and product forms, maximize the input–output efficiency of production factors, and motivate enterprises [1,2]. As well as improving efficiency and quality, digital transformation creates more business opportunities and competitive advantages for enterprises [3]. Moreover, digital technology has systematically been used to empower the transformation and upgrading of traditional industries [3]. In China, the digital economy has been developing rapidly in recent years. It has become an important driving force for the high-quality development of the country's economy, with the digital transformation of enterprises gradually becoming a mainstream trend [4]. The digital transformation and management of enterprises are also featured in a group of forward-looking and strategic development directions in the country's "14th Five-Year Plan." Facing the new trend of global digital economy development, the state and departments have issued several policies related to digital transformation. As urged in the "Proposal of the Central Committee of the Communist Party of China on Formulating the Fourteenth Five-Year Plan for National Economic and Social Development and the Long-term Goals for 2035" adopted by the Fifth Plenary Session of the 19th Central Committee of the Communist Party of China, digital development needs to be accelerated. However, various bottlenecks and difficulties are often involved, such as insufficient technology application and lack of talent [5,6].

Similarly, the digital level of the country's construction industry requires enhancement due to issues such as extensive production methods, low labor efficiency, and high energy/resource consumption. Strengthening forward-looking thinking and strategic deployment for digital transformation is crucial as digital transformation becomes a national strategic need for Chinese construction enterprises [2]. While transformation and upgrading are essential trends for construction companies, considering the existing challenges, careful planning is necessary to create effective digital transformation plans.

Establishing scientific evaluation models is also vital to analyze and improve digital transformation maturity, aiding enterprises' and governments' understanding of development status and supporting efficiency [7]. Constructing a digital transformation maturity assessment model can enhance efficiency and competitiveness, fostering innovation and customer experience. Creating a capability assessment model improves the strength of digital transformation: an awareness of weaknesses helps achieve targeted enhancement, furthering industry development [8]. Designing a capability assessment model sets an industry reference standard, boosting digital transformation [9] and enhancing enterprise competitiveness by improving efficiency, quality, and customer satisfaction through targeted measures [10]. Therefore, establishing a set of effective digital transformation maturity evaluation methods is very necessary. The establishment of an effective digital transformation maturity assessment model can not only meet the urgent demands of construction enterprises, but also help the government better understand the current situation of enterprise development and improve the efficiency of government guidance and support for enterprise development.

With this background, the objective of this study is to develop a digital transformation maturity model for the construction industry to identify the key issues that affect the digital transformation of construction enterprises and evaluate the digital transformation of enterprises [11,12]. The model consists of six primary indicators and twenty secondary indicators covering digital strategy, technology, data, organization, and change management, while also introducing a five-level digital maturity framework and a process for digital maturity assessment using the Analytic Hierarchy Process (AHP) and Decision Testing and Evaluation Laboratory (DEMATEL). A case study is also described in which the model is demonstrated and tested in a Chinese construction enterprise.

Our research questions are as follows:

RQ1. What aspects need to be considered to assess the digital transformation capabilities of construction companies?

RQ2. How can assessment indicators and weightings be determined to reflect the importance of different aspects?

The remainder of this paper is organized as follows: Section 2 explores digital transformation in construction enterprises, introducing maturity theory, exploring models, and proposing a comprehensive six-dimensional framework for the evaluation of their digital maturity; Section 3 presents our Digital Transformation Maturity Evaluation Model (DTCMM) alongside the utilization of the AHP and DEMATEL method for a comprehensive and accurate analysis of digital transformation maturity; Section 4 uses the AHP-DEMATEL method to analyze digital transformation maturity in construction enterprises, demonstrating progress and the need for enhancement through a questionnaire-based assessment; Section 5 explores the influence of digital transformation on construction firms, suggesting strategies for integrating technology, improving quality management, enhancing assessment models, and nurturing digital talent; finally, Section 5 provides our concluding remarks, including the main findings and implications, limitations of the study, and potential prospects for future research.

2. Literature Review

2.1. Digital Transformation of Construction Enterprises

Digital transformation refers to using digital and information technology to transform traditional business models, products, and services into digital forms to improve efficiency, reduce costs, and enhance customer experience and innovation capabilities [13]. Digital transformation refers to creating a digital world resembling the physical one, utilizing data, artificial intelligence, and cloud services. It involves optimizing and reconstructing organizational processes and talent culture to achieve business innovation and development supported by digital technology at the industry level. At the enterprise level, the focus of digital transformation is not limited to technology but also includes management methods, business models, and customer relationships, which require enterprises to design and implement changes [14]. At present, construction companies are actively promoting the process of digital transformation, which is mainly reflected in the wide application of BIM technology, intelligent equipment and systems, and data analytics and artificial intelligence. Although the digital transformation of construction enterprises has made some progress, it still needs to face many challenges. Zhen Jie (2012) [15] and others believe that the key to digital transformation lies in integrating digital technology with the enterprise's business. Kane et al. point out in the MIT's Sloan Management Review that there are currently two explanations for digital transformation: one is implementing and using innovative technologies; the other is that organizations use technology to conduct business in new and different ways. In the early days of enterprise digital transformation, most focused on the relationship between the application of internal management information systems deployed by enterprises and enterprise performance. Today, studies focus on the composition of digital capabilities and the resource pickup and orchestration process required for digital transformation.

Abundant research has taken place in China on the digital transformation of construction enterprises. For example, Zhu Feifei and Yan Xiaoli (2022) [16] propose that the digital transformation of construction enterprises is an in-depth integration of digital technology with enterprise management, production and construction, and project operation and construction. The result is a data-driven and innovative remodeling of strategy, organization, and internal resources in a dynamic external environment. Gong Yinyin, Duan Zongzhi (2022) [17], and others analyze the factors driving construction enterprises in the initiation, implementation, and synergy stages of digital transformation. They divide enterprises into large, small, and medium-sized; refine these factors; and propose key paths for different scales to implement digital transformation successfully. Zhou Zhiming et al. point out that enterprises in different lifecycle stages should adopt different digital transformation models. Taken as a whole, research in this field still focuses on the key factors of digital transformation, while quantitative research into digital-level evaluation methods still needs to be improved.

2.2. Maturity Theory

Maturity can be defined as the degree of operational capability and management level of an organization or enterprise in a particular field or aspect (Janicki and Tomasz, 2014) [18]. Usually, maturity assessment evaluates and grades an organization's or enterprise's maturity by comparing the business processes, working methods, technology application, personnel quality, and other aspects of a particular field or issue with best practices, industry, and national standards. Maturity grading is usually divided into five or six levels, which are gradually progress from beginner to advanced. This reflects the different degrees of operational capability and management level of an organization or enterprise in a particular field or aspect. It also provides it with goals and directions for growth and improvement. Maturity is a relatively new evaluation method and has a wide range of applications in many fields. Even within the same professional field, the understanding of maturity varies. Shehzad et al. [19] believe that entities (organizations and human beings) must go through different growth or maturity level stages before reaching full maturity. In particular, an organization's stages have three main unique attributes: they are continuous, progressing at a level that cannot easily be reversed, and involve a wide range of organizational activities and structures. Mettler et al. [20] point out that maturity is an evolutionary process from the initial to the final stage that is expected or normal. This definition emphasizes the maturation process and introduces another important concept: a growth or maturity stage. The five stages of quality management level proposed by Lahrmann et al. [21] in the U.S. from the perspective of enterprise quality management based on maturity theory lay the theoretical foundation for the maturity model [21]. To summarize, we can identify several basic characteristics of maturity theory: an organization or enterprise's operational capabilities and management level in a particular field go from the initial stage to achieving an expected or normal final stage. The final stage is a continuous, non-reversible level of this evolutionary process (each stage should be divided according to the stage characteristics of the evolutionary process).

The Capability Maturity Model evolved based on maturity theory, but its practical application originated in the computer software industry [22,23]. The model, abbreviated as SW-CMM or CMM, was successfully developed by the Software Engineering Institute of Carnegie Mellon University in 1987 [24]. It is the world's most popular and practical software production process standard and software enterprise maturity level certification standard, describing each development stage in the practice of software organizations in defining, implementing, measuring, controlling, and improving their software processes [25]. The core of the CMM is to treat software development as a process and, according to this principle, conduct process monitoring and research into software development and maintenance to make it more scientific and standardized and enable enterprises to achieve business goals better [26]. Except for the initial level, the five levels of the model can be decomposed into specific key practical processes that must be achieved in order to proceed to the next level. Each key process contains many common characteristics to guide the organization to achieve project goals in key processes [27]. With the continuous development and evolution of the CMM, its application field has become wider and wider. After many practical applications, experts and scholars in various fields have begun to focus on the model. After its improvement and optimization by experts and scholars in other fields, a number of CMM applications have emerged [28]. For example, Wang Haiqiang of the Harbin Institute of Technology and others proposed their Construction Supply Chain Performance Maturity Model (CSCMM) [29]. To evaluate construction supply chain performance based on the maturity model, an increasing number of industries and fields apply this model. Its purpose is to describe an object's development direction, development stage, and characteristics. Therefore, the general process of evaluating capability maturity includes selecting the key process areas of the model, constructing an evaluation index system, identifying key activities, and dividing the development stage into five to ten stages.

2.3. Digital Maturity Models

Major consulting companies worldwide were the first major initiators of research into enterprise digital maturity. In the early days, they mostly focused on the key factors of digital transformation, centering qualitative research. For example, in its 2013 digital transformation survey, IBM proposed that there are three main strategic approaches to enterprise digital transformation: reshaping customer experience, focusing on value positioning; reshaping operation models, focusing on value delivery; and combining the first two approaches while transforming customer value propositions and operational delivery methods. The Accenture consulting company also proposed that the digital transformation of enterprises can be divided into three dimensions: digital business innovation, digital marketing, and digital operations. In the "Notice on Accelerating the Digital Transformation of State-owned Enterprises" issued by the State-owned Assets Supervision and Administration Commission of the State Council, four transformation directions for enterprise digital transformation were proposed: product innovation digitalization, intelligent production and operation, agile user service, and ecologicalization of the industrial system. After the concept of digital transformation gradually became familiar and applied, some consulting companies and research institutions have successively researched digital maturity models for enterprises, as summarized in Table 1.

Table 1. Domestic and international maturity evaluation models.

Researcher	Model Name	Dimensions Covered	Class Names
China Electronics Standardization Institute	Intelligent Manufacturing Capability Maturity Model	Design, production, logistics, sales, service, resource elements, interconnection, system integration, information integration, emerging business formats	Planned level, specification level, integration level, optimization level, leading level
Wang Rui	Digital Maturity Evaluation Model of Manufacturing Enterprises	Strategy, operational technology, cultural organization capability, ecosystem	Digital starter, digital upgrader, digital transformation, digital mature player, digital leader
LICHTBLAU K	IMPLUS-Industrie 4.0 Readiness	Strategy and organization, smart factory, efficient operations, smart products, data-driven services, employees	Layperson, beginner, intermediate, experienced, expert, top player
Zhu Hongcan, Fang Xinyue	Government data open API ecosystem maturity assessment model	Data quality assessment, portal function optimization, portal navigation design, map navigation design, data analytics design, information retrieval design, data statistics design	Construction starts. Function complete Application extension Professional deep cultivation data ecology
McKinsey Company	Digital Media Maturity Model	Strategy, IT capabilities, culture, organization, and talent	Evolvers, market matchers, digital strivers, digital disruptors, ecology
LEYH C	SIMMI 4.0	Vertical integration, horizontal integration, digital product development, cross-sectional technical standards	Basic digitization, cross-departmental digitization, horizontal and vertical digitization, full digitization, optimized full digitization
Leino	VTT Model of Digimaturity	Strategy, business model, customer impact, organization and process, talent and culture, IT	System shaper beginner, normative level, management level, excellent

Most studies use the key elements of classic maturity models, such as strategy, organization, talents, and technology. Most cover four to six dimensions, but there are also many differences between them regarding the design of specific key elements. For example, in terms of scope of application, some models are suitable for describing the level of digital penetration within a single enterprise, and some are suitable for enterprise clusters with common evolutionary characteristics. Most research methods use qualitative methods, generally formulated and selected based on interviews. The models' key process areas and indicators often need more scientific theoretical support, and their problems need to be more comprehensive. However, the possible application value of an evaluation model suitable for a single enterprise is limited to that specific enterprise, and it is not universal. Studies of digital maturity assessment models have achieved much in the theoretical research and practical application of digital maturity. These achievements help understand enterprises' current positioning and clarify potential action. Therefore, a more theoretical basis for sustainable application may be needed in the subsequent improvement and application process. Second, in most cases, the model's scope is within the enterprise and only considers the internal perspective, not the business ecosystem and its stakeholders, the relationship between the parties, nor the need for digital measures of the supporting activities of the enterprise value chain. Third, few models consider the performance of enterprise digitalization and digital security construction as evaluation dimensions. These deficiencies are detrimental to the continuous improvement and popularization of these models, greatly reducing their application value.

To summarize, it is apparent that digital transformation is based on emerging technologies such as 5G, the Internet of Things, and cloud computing to optimize, innovate, and reshape construction enterprises' business processes and process technologies. The purposes of ensuring quality, reducing costs, and increasing efficiency and environmental protection are achieved through optimizing and transforming various processes. Previous research shows that enterprise digital transformation is not limited to the application of digital technology but also involves cultural and organizational changes. Enterprise digital maturity assessment architecture is a method designed by PricewaterhouseCoopers (PwC) in the United Kingdom to assist enterprises in identifying their current digital transformation situation, formulating more effective plans, and enhancing the efficiency and success rate of their digital transformation programs. PwC believes that the leading indicator, "digital strategy" is the first point; business application results are the second point; and "digital business application" and the remaining four dimensions (3–6) are supporting elements. Each dimension can be subdivided into several subdimensions.

Therefore, according to PwC's enterprise digital maturity assessment framework, the present study evaluates the digital maturity of construction enterprises through six dimensions: strategic guidance, business application results, technical capability support, data capability support, organizational capability support, and digital transformation (Figure 1).

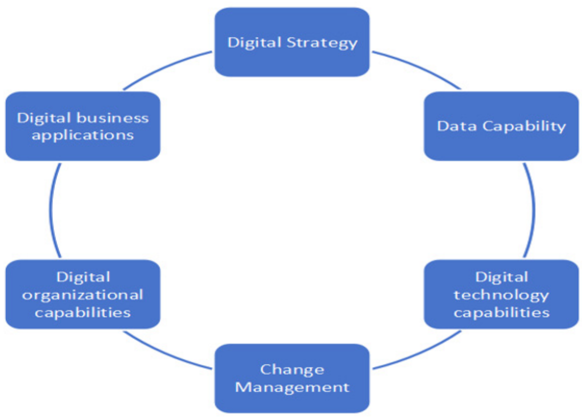

Figure 1. PwC's enterprise digital maturity assessment architecture.

3. Construction of the Digital Transformation Maturity Evaluation Model (DTCMM) for Construction Enterprises

3.1. Construction of the DTCMM Evaluation Model

Following the guidelines of the PwC framework for assessing enterprise digital maturity, the present research develops a digital maturity evaluation model for the construction industry, as illustrated in Figure 1. The model aims to encompass all aspects of digital transformation within construction enterprises. Given the diverse professional fields of Chinese construction companies, specific indicators can be adjusted in practice to achieve optimal outcomes.

3.2. Description of Specific Indicators

3.2.1. Digital Strategy

Digital strategies can be grouped into distinct categories: the alignment level (A1) of digital strategic planning; the commitment level (A2) of implementing digital transformation; and the extent of government policy support (A3). The alignment level (A1) assesses whether an enterprise's digital transformation strategy corresponds to its long-term goals and technical capabilities, emphasizing the need for a tailored strategy to enhance efficiency and clarity [30]. The commitment level (A2) gauges an enterprise's determination and vigor in executing its digital transformation strategy [31]. As digital transformation is gradual, an enterprise's support significantly impacts its pace and effectiveness [32]. Greater investment signals stronger commitment, fostering more effective leadership and supervision of the transformation process [33]. Governmental policy support (A3) reflects resource allocation for digital transformation by the enterprise's local government department, indicating government encouragement [34].

3.2.2. Digital Business Applications

Digital business applications are classified into four groups: human resource planning (B1), business contract management (B2), production technology management (B3), and quality and safety management (B4). Human resource planning (B1) assesses the existence of a comprehensive human resource information management system, enhancing decision-making, personnel deployment, cost efficiency, and overall human resource structure analysis [35]. Business contract management (B2) evaluates material and business proficiency, which includes contracts, costs, materials, subcontractors, and settlement management, driving productivity, cost reduction, competitive advantage, and overall benefits [36]. Production technology management (B3) evaluates the integration of information technology, like IoT, big data, digital twins, and BIM, into construction site management, enhancing on-site capabilities and competitiveness [37]. Quality and safety management (B4) assesses real-time tracking of project quality and safety indicators, spanning monthly quality reports, inspections, analysis, statistics, and safety measures, fostering high-quality development through quality, safety, and facility management [38].

3.2.3. Digital Technology Capabilities

The category of digital technology capabilities is segmented into five sections: new technical personnel (C1), digital infrastructure (C2), degree of improvement of digital project integration management platforms (C3), degree of integration of digital technology into construction sites (C4), and digital innovation iteration ability (C5). New technical personnel (C1) signifies an enterprise's human resource reservoir, where employees experienced in digital system development or operational processes play a pivotal role in enhancing digital technology capabilities. Digital infrastructure (C2) denotes the enhancement of foundational IT infrastructure, including 5G networks, as a complete infrastructure expedites the implementation of digital technology due to its high hardware and software prerequisites [39]. The degree of improvement of digital project integration management platforms (C3) reflects an enterprise's familiarity with project lifecycles as a whole, while an all-encompassing management platform amplifies productivity [40]. The degree of integration of digital technology into construction sites (C4) highlights whether digital transformation results suit the needs of construction sites, align with smart construction site functions, and effectively combine digital technology with construction tools. Digital innovation iteration ability (C5) underlines R&D innovation competence and adeptness in terms of timely software updates [41].

3.2.4. Data Capabilities

Data capabilities are divided into three sections: data collection and processing (D1), data analytics capability (D2), and data security (D3). Data collection and processing (D1) assesses if an enterprise gathers comprehensive and real-time data and if the data it obtains are the most representative [42]. Data analytics capability (D2) gauges whether the enterprise comprehensively and logically interprets the collected data, ensures accurate data comprehension, and effectively mines information from the data [43]. Data security (D3) signifies the enterprise's measures to safeguard data securely and in compliance with the law, including continuous security maintenance, which covers the security of both data sources and data protection [44].

3.2.5. Digital Organizational Capabilities

Digital organizational capabilities encompass three factors: organizational mechanisms and the process of enterprise digitalization (E1), corporate culture (E2), and employees' commitment to digital transformation (E3) [45]. Organizational mechanisms (E1) gauge the alignment of an enterprise's structure with digital transformation and the feasibility of long-term digital projects. Corporate culture (E2) mirrors decision-makers' stance on innovation, which can range from conservative to innovative. Diverse cultures influence transformation decisions [41]. Employees' commitment to digital transformation (E3) impacts transformation efficiency and progress; heightened employee engagement enhances overall transformation quality and efficiency [46,47].

3.2.6. Change Management

Change management encompasses digital transformation management mode (F1) and change manager skills (F2). Digital transformation management mode (F1) evaluates the effectiveness of an enterprise's oversight and control over digital transformation to address potential issues [17]. Change manager skills (F2) assess whether employees are well versed in the entire transformation process and capable of identifying and promptly addressing potential or ongoing issues in change management [48] as summarized in Table 2.

Table 2. List of factors influencing the maturity of digital transformation in the construction industry.

	Primary Factor	Number	Secondary Factor	Number
Evaluation model of digital transformation maturity of construction enterprises (A)	Digital strategy	B1	Degree of matching digital strategic planning	C11
			Intensity of enterprise's promotion of digital transformation	C12
			Strength of government policy incentives and support	C13
	Digital business applications	B2	HRM	C21
			Business contract management	C22
			Productive technology management	C23
			Quality and safety management	C24
	Digital technology capabilities	B3	New technical personnel	C31
			Digital infrastructure	C32
			Degree of functioning of digital management platform	C33
			Degree of integration of digital technology into construction sites	C34
			Digital innovation and iteration ability	C35
	Data capabilities	B4	Data collection and processing capacity	C41
			Data analysis ability	C42
			Data security	C43
	Digital organizational capabilities	B5	Digital organizational structure and processes	C51
			Corporate culture	C52
			Degree of employee digital transformation	C53
	Change management	B6	Digital management mode	C61
			Change management staff skills	C62

3.3. Maturity Level

Digital transformation maturity in the construction industry represents an entity's or third-party evaluation unit's understanding of its ongoing digital transformation status [49]. It gauges how well an enterprise can define, control, predict, and continuously enhance its digital transformation process. This comprehensive assessment incorporates various indicators of digital transformation [50]. The model, informed by preceding evaluation methods and pre-experiment outcomes, categorizes enterprises on similar digital levels into five categories: business management, process operation, smart construction, intelligent scenario application, and industrial ecological coordination. The business management stage, from 0 to 0.8, emphasizes integrating business systems for collaboration and information sharing, though data application remains low [51]. In the range of 0.8 to 1.6, process operation focuses on integrating digital technology to enhance enterprise management, operations, and strategic planning [52]. The interval of 1.6 to 2.4 targets intelligent construction, emphasizing quality, safety, and efficiency improvements through technology integration [53]. From 2.4 to 3.2, the intelligent scenario application level employs data analytics, BIM, and AI to optimize project management. Lastly, the range of 3.2 to 4.0 pertains to industrial ecological collaboration, wherein enterprises leverage their digital capabilities to build a digital engineering ecosystem, fostering efficient coordination across the industry chain and creating a comprehensive digital industry ecology.

3.4. Selection of Evaluation Methods

The Analytic Hierarchy Process (AHP) and Decision-Making and Trial Evaluation Laboratory (DEMATEL) method is a hybrid approach combining the AHP and DEMATEL techniques to tackle multidimensional decision-making and complex system analysis [54]. The AHP structures the target into hierarchical layers, decomposing criteria into index factors for a layered model. This approach evaluates the importance and weight of lower-level factors towards upper-level goals through a cascading analysis. For instance, it computes the influence of six aspects at the criterion layer on the construction industry's digital transformation at the target layer. Then, it gauges the decision-making layer's impact on the criterion layer's six aspects. However, the AHP lacks accounting for mutual influence among the 20 factors, focusing solely on weighted relationships between the layers and disregarding interactions between the influencing factors [55]. For instance, the support of policy incentives from government departments impacts the intensity of enterprises' digital transformation and the functionality of digital infrastructure and digital project integration platforms under the digital technology capability criterion layer.

Conversely, integrating digital technology into construction sites and production technology management also affects the support of policy incentives from government departments. To address this, the DEMATEL method is employed to refine the degrees of influence of the 20 factors on the construction industry's digital transformation. DEMATEL assesses how each factor in the system impacts others, constructs a system impact matrix, and calculates degrees of influence and relationships among factors. Subsequently, these degrees of influence and relationships are summed up to determine the centrality of each factor. The AHP-DEMATEL approach combines the base weights of the 20 factors with their degrees of influence and centrality to yield comprehensive influence weights. This methodology rectifies AHP's oversight of mutual influence among factors and mitigates DEMATEL's shortcomings in terms of hierarchical calculations of equivalent weights, thereby ensuring calculation precision [56,57].

4. Analysis of Influencing Factors of Construction Enterprise Digital Transformation Maturity Based on AHP-DEMATEL

4.1. Specific Steps of the AHP Method

4.1.1. Building Hierarchical Models

This study focuses on large-scale construction enterprises primarily involved in municipal public works and housing construction projects, also encompassing areas like roads, bridges, and tunnels. These enterprises are extensively engaged in architectural, structural, and mechanical–electrical design. They are capable of undertaking diverse construction projects and offering top-notch services and solutions. By organizing indicator relationships and considering enterprise realities and the scope of our research, a digital transformation maturity evaluation model for construction enterprises is established by classifying indicators into the target and criterion layers.

4.1.2. Determination of Judgment Matrix

This study assembled a panel of experienced experts to conduct pairwise comparisons between influencing factors from the criterion and factor layers, assigning them importance scores on a scale of 1 to 5 (refer to Table 3). Subsequently, an influence factor judgment matrix A = *i*, *j* = 1, 2, . . ., *n* was formulated, where A represents the importance of element *i* within the same criterion or factor layer relative to element *j* (as displayed in Table 3). Table 4 serves as an evaluation system for judgment matrix A.

Table 3. Scaling meanings.

Scale $\overline{a_{ij}}$ Score	Scale Description
5	Comparing element *i* and element *j*, element *i* is extremely important
4	Element *i* is more important than element *j*
3	Comparing element *i* and element *j*, element *i* is significantly more important
2	Element *i* is slightly more important than element *j*
1	Element *i* has the same degree of influence as element *j*
1/2	Element *i* is slightly less important than element *j*
1/3	Element *i* is much less significant than element *j*
1/4	Comparing element *i* and element *j*, element *i* is very unimportant
1/5	Comparing element *i* and element *j*, element *i* is extremely unimportant

Table 4. Judgment matrix A.

Level 1 Indicators	B1	B2	B3	B4	B5	B6
B1	1	1/3	1/2	1/2	1	1
B2	3	1	1	2	3	3
B3	2	1	1	1	2	2
B4	2	1/2	1	1	2	2
B5	1	1/3	1/2	1/2	1	1
B6	1	1/3	1/2	1/2	1	1

4.1.3. Computing Eigenvalues and Eigenvectors

The sum product method was used to obtain the eigenvalues λmax and eigenvector W of judgment matrix A. The vector value corresponding to the eigenvector is the weight of each element relative to the upper element. The calculation steps are:

(1) Normalize each column in the judgment matrix to obtain $\overline{a_{ij}}$;

$$\overline{a_{ij}} = \frac{a_{ij}}{\sum_{k=1}^{n} a_k}, (i, j = 1, 2, \cdots, n)$$

(2) Add the normalized elements in rows to obtain vector $\overline{W} = (\overline{W_1}, \overline{W_2}, \cdots \overline{W_n})^T$;

$$\overline{W_i} = \sum_{j=1}^{n} \overline{a_{ij}}, (i, j = 1, 2, 3, \cdots)$$

(3) Perform a normalization process to obtain eigenvector $W = (W_1, W_1, \cdots W_n)^T$;

$$W_i = \frac{\overline{W_i}}{\sum_{i=1}^{n} \overline{W_i}}$$

Calculate eigenvector $W_i = (0.597, 1.772, 1.29, 1.147, 0.597, 0.597)^T$;

(4) Calculate the characteristic roots;

$$U = AW$$

$$U = \begin{pmatrix} 1 & 1/3 & 1/2 & 1/2 & 1 & 1/2 \\ 3 & 1 & 1 & 2 & 3 & 3 \\ 2 & 1 & 1 & 1 & 2 & 2 \\ 2 & 1/2 & 1 & 1 & 2 & 2 \\ 1 & 1/3 & 1/2 & 1/2 & 1 & 1 \\ 2 & 1/3 & 1/2 & 1/2 & 1 & 1 \end{pmatrix} \times \begin{pmatrix} 0.597 \\ 1.772 \\ 1.29 \\ 1.147 \\ 0.597 \\ 0.597 \end{pmatrix} = \begin{pmatrix} 3.600 \\ 10.729 \\ 7.791 \\ 6.905 \\ 3.600 \\ 3.600 \end{pmatrix}$$

(5) Calculate the maximum eigenvalue of judgment matrix A λmax.

$$\lambda max = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i}$$

$$\lambda max = \frac{1}{n}\Sigma\sum_{i=1}^{n}\frac{(AW)_i}{W_i} = \frac{1}{6}\left(\frac{3.6}{0.597} + \frac{10.729}{1.772} + \frac{7.791}{1.29} + \frac{6.905}{1.147} + \frac{3.6}{0.597} + \frac{3.6}{0.597}\right) = 6.034$$

4.1.4. Leveling Single-Order Consistency Check

A consistency index (CI), consistency ratio (CR), and average random one-time index (RI) were introduced. When CR < 0.1, the consistency test of the index is satisfied. RI values are shown in the Table 5, and n is the order of the judgment matrix.

$$CI = \frac{(\lambda max - n)}{(n-1)} = \frac{6.034 - 6}{6 - 1} = 0.0068$$

Table 4 shows that when $n = 6$, the RI value is 1.26.

$$CR = \frac{CI}{RI} = \frac{0.0068}{1.26} = 0.0054 < 0.1$$

Therefore, the random one-time ratio CR = 0.0054 < 0.1 meets the consistency requirement.

Table 5. Values of different orders of RI.

N Order	3	4	5	6	7	8	9	10	11
RI value	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52

4.1.5. Calculation of Weights

The weight of the criterion layer concerning the target layer and the weight of the factor layer concerning the criterion layer were computed. The index weight of the criterion layer forms a feature vector, and the factor layer's weight relative to the criterion layer is directly given here. Subsequently, the weights associated with each target layer factor were multiplied by the criterion layer's weight to derive the basic weights of each factor in the factor layer, denoted as W^1.as summarized in Table 6.

Table 6. Basic weights of primary indicators.

Primary Metric	Digital Strategy (B1)	Digital Business Applications (B2)	Digital Technology Capabilities (B3)	Data Capabilities (B4)	Digital Organizational Capabilities (B5)	Change Management (B6)	Weight (%)
Digital Strategy (B1)	1	1/3	1/2	1/2	1	1	9.95
Digital Business Applications (B2)	3	1	1	2	3	3	29.53
Digital Technology Capabilities (B3)	2	1	1	1	2	2	21.50
Data Capabilities (B4)	2	1/2	1	1	2	2	19.11
Digital Organizational Capabilities (B5)	1	1/3	1/2	1/2	1	1	9.95
Change Management (B6)	1	1/3	1/2	1/2	1	1	9.95

λmax = 6.034, CI = 0.0068, RI = 1.26, CR = 0.0054 < 0.1. Values pass the random consistency test.

4.1.6. Calculation of Weight of Indicators at All Levels

The AHP was used to calculate the weight of the comprehensive evaluation index system as summarized in Table 7.

Table 7. Weights of the comprehensive evaluation index system W^1.

Standard Layer (Primary Index)	Weight (%)	Index Layer (Secondary Index)	Weight (%)	Base Weight W^1 (%)
B1	9.95	C11	49.05	4.88
		C12	19.76	1.97
		C13	31.19	3.10
B2	29.53	C21	16.46	4.86
		C22	20.63	6.09
		C23	34.17	10.09
		C24	28.75	8.49
B3	21.50	C31	13.51	2.90
		C32	7.85	1.69
		C33	12.71	2.73
		C34	39.60	8.51
		C35	26.33	5.66
B4	19.11	C41	31.19	5.96
		C42	49.05	9.37
		C43	19.76	3.78
B5	9.95	C51	31.19	3.10
		C52	19.76	1.97
		C53	49.05	4.88
B6	9.95	C61	66.67	6.63
		C62	33.33	3.32

4.2. DEMATEL Method-Specific Steps

4.2.1. Determination of Initial Impact Matrix

Using the list of influencing factors from Table 2 in the construction industry's digital transformation maturity assessment model, a questionnaire was formulated and distributed to 25 experts engaged in digital transformation within the construction sector and to researchers in related fields. The experts scored the degree of interaction between the influencing factors, following a scale of 0—no impact, 1—little impact, 2—moderate impact, 3—large impact, and 4—strong impact. After processing the questionnaire data, the initial direct impact matrix D for influencing factors within the digital transformation maturity assessment system was established.

4.2.2. Determination of Normalized Impact Matrix

Following the analysis of questionnaire data, the relationship matrix A for influencing factors in the construction industry's digital transformation was formulated. The initial direct impact matrix A was normalized to obtain normative impact matrix B from $B = A/\max(\sum_{j=1}^{n} a_{ij})$.

4.2.3. Determination of Comprehensive Impact Matrix

Considering the direct influence and indirect influence between the factors, the operation of accumulating indirect influence and direct influence was adopted, using the formula $T = B + B^2 + B^3 + \ldots B^n$. When $n \to \infty$, comprehensive influence matrix T can be approximated as $T = B(I - B)^{-1}$.

4.2.4. Computing Centrality and Causality

Utilizing the formulae $D_i = \sum_{j=1}^{n} t_{ij}$, $(i = 1, 2, 3, \ldots, n)$ and $C_i = \sum_{i=1}^{n} t_{ij}$, $(i = 1, 2, 3, \ldots, n)$, influence degree values D and C were computed for each influencing factor, where D represents the row sum and C represents the column sum. Subsequently, centrality M (D + C) and causal degree value D − C were calculated for each influencing factor. Table 8 shows the results.

Table 8. Centrality and weight of each influencing factor.

	Influence Degree d	Influence Degree c	Centra d D + C	Weight
C11	2.155	1.978	4.133	0.052
C12	2.267	2.215	4.482	0.056
C13	1.664	1.6	3.264	0.041
C21	1.773	2.429	4.202	0.052
C22	1.742	2.656	4.397	0.055
C23	1.961	2.613	4.573	0.057
C24	1.947	2.51	4.458	0.056
C31	2.978	1.892	4.87	0.061
C32	2.864	1.718	4.581	0.057
C33	2.341	2.275	4.616	0.058
C34	2.543	1.938	4.481	0.056
C35	2.561	1.866	4.427	0.055
C41	2.268	2.118	4.387	0.055
C42	2.492	2.269	4.761	0.059
C43	1.629	1.88	3.508	0.044
C51	1.369	1.277	2.646	0.033
C52	1.108	1.236	2.344	0.029
C53	1.486	2.834	4.32	0.054
C61	1.519	1.66	3.18	0.04
C62	1.357	1.061	2.418	0.03

4.3. Calculation of AHP-DEMATEL Combination Weights

By incorporating fundamental weights W^1 from each AHP index and centrality M, the comprehensive impact degree obtained by DEMATEL is multiplied by the basic weights of each index. The combined weight Z of the influencing factors is then computed by:

$$Z = \frac{M_i \times W^1}{\sum_{j=1}^{n} M_i \times W^1}, i = 1, 2 \ldots n$$

Table 9 shows the resulting combined weights for each index derived from the AHP-DEMATEL method.

Table 9 shows that the indices' weights signify expert consensus. For instance, among primary indicators, digital business applications hold a significant share of up to 29.53%, signifying their importance in representing the digital maturity of the current supply chain. Quality and safety management, crucial aspects in construction, have the highest weight among the corresponding secondary indicators. This is due to their direct impact on external performance and ultimate transformation goals. Digital technology capabilities' weight in primary indicators follows closely behind that of digital business applications, owing to new technical personnel, digital infrastructure, integration of digital technology into construction sites, and digital innovation iteration ability. These factors demonstrate how emerging digital technologies align and interact with the construction industry. New technical personnel, ranking first among secondary indicators, is a notable contributor, reflecting the human resource reservoir and proficiency in digital system development.

Table 9. Combination weight of each indicator Z.

	Base Weight W^1	Centra d M (%)	Combination Weight z (%)
C11	4.88	5.2	4.90
C12	1.97	5.6	2.13
C13	3.10	4.1	2.45
C21	4.86	5.2	4.88
C22	6.09	5.5	6.46
C23	10.09	5.7	11.10
C24	8.49	5.6	9.17
C31	2.90	6.1	3.41
C32	1.69	5.7	1.86
C33	2.73	5.8	3.05
C34	8.51	5.6	9.19
C35	5.66	5.5	6.01
C41	5.96	5.5	6.32
C42	9.37	5.9	10.67
C43	3.78	4.4	3.21
C51	3.10	3.3	1.97
C52	1.97	2.9	1.10
C53	4.88	5.4	5.08
C61	6.63	4	5.12
C62	3.32	3	1.92

4.4. Comprehensive Assessment Calculation Method

To ensure the accurate measurement of each domain's implementation level, the questionnaire comprised one to five questions per domain, with respondents assigning scores of 0 to 4 to both their digital level and importance. Averaging valid questionnaire domain scores yielded comprehensive domain scores. Consider a construction company specializing in roads, bridges, tunnels, and housing. The company was among the first to use digital technology due to national policies. In adopting digital methods, it encountered various challenges, making it a good representation of the construction industry in China. The company's efforts to enhance its digital capabilities focused on areas like managing construction (including quality, safety, and progress), using smart construction sites, and integrating Building Information Modeling (BIM). The company collaborated with parties like supervisors, builders, and testers. They built a comprehensive digital platform that connected all parts of the construction process from start to finish. This helped digitize and make construction management smarter in terms of controlling costs, tracking progress, ensuring quality, maintaining safety, and monitoring the environment. By combining technologies like BIM, Geographic Information Systems (GIS), the Internet of Things (IoT), and mobile Internet, the company managed on-site personnel, machinery, materials, production processes, and more in real time. They used data collection and analysis to monitor, analyze, and mine information automatically. This enabled real-time monitoring, early warnings, safety checks, performance evaluations, and quick emergency response. We conducted a detailed, comprehensive assessment of the company's influencing factors at all levels based on the questionnaire and derived a composite score S for each domain from the above rules for scoring values for each domain (Table 10).

Table 10. Weights and scores of each index of the digital maturity evaluation model for the case enterprise.

Primary Metric	Single-Layer Weight (%)	Secondary Metric	Single-Layer Weight (%)	Foundation Weight (%)	Assembled Weight (%)	Synthesized Grade	Assembled Grade
Digital strategy (B1)	9.95	C11	49.05	4.88	4.90	2.2	0.108
		C12	19.76	1.97	2.13	1.8	0.038
		C13	31.19	3.10	2.45	2.6	0.064
Digital business applications (B2)	29.53	C21	16.46	4.86	4.88	2	0.098
		C22	20.63	6.09	6.46	2.2	0.142
		C23	34.17	10.09	11.10	1.2	0.133
		C24	28.75	8.49	9.17	1.2	0.110
Digital technology capabilities (B3)	19.11	C31	13.51	2.90	3.41	0.8	0.027
		C32	7.85	1.69	1.86	2.0	0.037
		C33	12.71	2.73	3.05	1.0	0.031
		C34	39.60	8.51	9.19	1.0	0.092
		C35	26.33	5.66	6.01	0.8	0.048
Data capabilities (B4)	18.99	C41	31.19	5.96	6.32	0.6	0.038
		C42	49.05	9.37	10.67	0.6	0.064
		C43	19.76	3.78	3.21	0.8	0.026
Digital organizational capabilities (B5)	9.95	C51	31.19	3.10	1.97	1.6	0.032
		C52	19.76	1.97	1.10	1.4	0.015
		C53	49.05	4.88	5.08	1.2	0.061
Change management (B6)	9.95	C61	66.67	6.63	5.12	1.0	0.051
		C62	33.33	3.32	1.92	0.8	0.015

As the calculated overall digital maturity score for the example enterprise is 1.23, it is evident that the enterprise is currently at the process operation stage in its digital transformation journey. This implies that the company uses digital technology to integrate the property, finance, and taxation aspects, aiming to enhance its operational quality and capabilities continuously. The company utilizes intelligent data analysis and early risk warning to support strategic planning, risk management, target setting, performance evaluation, and decision-making. However, there is room for improvement in terms of its digital capabilities, which as of now limit the company's growth potential. To progress further, a deeper and more comprehensive digital transformation is necessary. Within the construction management process, digital technology is employed to reduce construction timelines, lower costs, enhance project quality, and expedite the move toward intelligent construction practices.

5. Conclusions

This study uncovered significant insights using the AHP-DEMATEL method to develop a digital transformation maturity evaluation model tailored to construction enterprises. The analysis highlighted specific influential factors that substantially impact the digital transformation process within construction enterprises. These factors, encompassing new technical personnel, digital infrastructure, digital innovation iteration ability, and the integration of digital technology into construction sites, serve as crucial determinants for shaping effective digital transformation strategies within the construction industry. Moreover, this study emphasizes the critical importance of integrating digital technology into construction sites in practice. This symbiotic relationship not only enhances operational efficiency but also elevates the overall quality of production. This underscores the notion that digital transformation's success is contingent upon its alignment with the real-world operational complexities of construction sites, as well as highlighting the significance of digitizing production technology management and quality and safety management through the incorporation of advanced digital technologies. This includes the adoption of process planning systems and production planning control systems to enhance production efficiency and product quality within construction enterprises.

5.1. Comprehensive Impact Analysis

The weights assigned to each indicator reflect consensus among experts. For instance, digital business applications hold the largest weight, of 29.53%, among primary indicators. This indicator is the most representative of construction enterprises' digital maturity at this stage compared to other primary indicators. Among secondary indicators, production technology management and quality safety management received the highest weights. These aspects are pivotal in the digital transformation of construction firms. Given the complexity and risks inherent in the construction industry, effective production technology management and quality safety management are crucial for project smoothness, timely delivery, and risk mitigation.

Digital transformation enables automation, digitization, and lean management throughout construction. This leads to improved work efficiency, enhanced quality, heightened core competitiveness, and increased enterprise market share. The weight of digital technology capabilities ranks second among primary indicators, just behind digital business applications. This is due to the significance of new technical personnel, digital infrastructure, the functional completeness of digital project integration management platforms, the level of integration of digital technology into construction sites, and the iterative potential of digital innovation. Notably, the degree of integration of digital technology into construction sites, denoted as C34, holds the third position among secondary indices, with a weight of 9.19%.

The application of digital technology within construction enterprises spans various areas, encompassing BIM, virtual reality technology, the Internet of Things, cloud computing, and more. While it offers substantial benefits, its implementation sometimes needs to be more consistent between technological advancements and managerial readiness. Moreover, achieving a high level of integration between digital technology and construction sites significantly enhances the efficiency and manageability of the entire production process. This underscores the importance of integrating digital technology and construction sites in enterprise digital transformation.

5.2. Analysis of the Interaction between Factors

Regarding impact, the key factors are C31 (new technical personnel), C32 (digital infrastructure), C35 (digital innovation ability), and C34 (digital technology and construction site integration). These four factors strongly influence other aspects. To start, digital transformation needs skilled technical staff for its success. Having the right people with technical knowledge is crucial. If a company has skilled technical employees, it is easier to achieve successful digital transformation.

Similarly, digital transformation relies on advanced technologies like cloud computing, big data, and AI. However, these need a solid foundation, or infrastructure, to work well. If a company's digital infrastructure needs to be improved, digital transformation becomes challenging. Moreover, a successful digital transformation requires continuous innovation to meet market needs and user expectations. If innovation is lacking, digital transformation stagnates. Also, digital technology must be seamlessly integrated into construction sites for a digital transformation to work. If this integration weakens, the results of digital transformation will differ from what is expected. These factors—new technical personnel, digital infrastructure, innovation ability, and integration with construction sites—are the most influential in assessing digital transformation maturity in construction companies. To improve digital transformation, these areas need focus.

Regarding the degree of influence, the most impactful indicators are C53 (employee engagement), C22 (business contract management), and C23 (production technology management). Other factors are greatly influenced by these three. Employee engagement plays a major role, showing that employees are crucial participants in and promoters of digital transformation. This means that, to succeed, companies must value employee positivity and involvement and guide them in embracing digital transformation.

In terms of centrality, the most significant indicators are C1 (new technical personnel), D2 (data analytics capabilities), C3 (digital project integration management platform), and C2 (digital infrastructure). These four indicators are important for digital transformation in construction and should be given more attention.

Regarding the degree of relationships, the top indicators are C1 (new technical personnel), C2 (digital infrastructure), C5 (digital innovation ability), and C4 (digital technology and construction site integration). These four indicators impact other aspects. By analyzing the centrality of these indicators, we realize the need to boost the recruitment and training of technical staff so employees can lead continuous improvements. This makes the digital transformation process smoother and better suited to expectations and real-world construction. Strengthening data analytics helps uncover insights from various datasets, improving decision-making. Enhancing the functions of digital project integration management platforms significantly improves production efficiency. All these steps are crucial for a successful digital transformation journey.

5.3. Recommendations for Digital Transformation

Blending digital tech with construction sites: While digital technology is vital for transformation, applying it to construction sites is equally important. Using tools like BIM (Building Information Modeling) helps combine digital tech and real-world construction, boosting efficiency and quality across the construction process.

Advanced production tech digitization: Managing production technology is key in construction. Digital tech can enhance the precision and efficiency of management. Introducing digital tools such as process planning systems and production planning control systems can greatly improve productivity and product quality.

Boosting quality and safety through digitization: Quality and safety management are pivotal for construction businesses. Using digital tech elevates these aspects. Businesses should embrace tools like intelligent inspection and safety monitoring systems to digitize quality and safety management, enhancing both levels.

Enhance digital transformation assessment: Digital transformation is complex. Establishing a sound assessment model guides companies. Constantly improving this model helps evaluate every aspect of transformation, aiding in implementation and optimization.

Nurture digital talent continuously: Achieving digital transformation requires skilled individuals. Building a robust digital talent pool is essential. Companies should foster and recruit digital talent, collaborating with universities and offering in-house training to enhance their quality and capabilities.

Furthermore, our research has illuminated the pivotal role of employees in driving the success of digital transformation endeavors. Employees' positive attitudes and active participation appear as indispensable factors for the effective implementation of digital transformation initiatives. This underscores the critical need for cultivating and engaging digital talent within construction organizations.

Establishing a digital transformation maturity model for the construction industry aims to determine the key aspects that affect the digital transformation of construction enterprises and evaluate this digital transformation. This allows project leaders to clarify the maturity stage of the company through the evaluation process and the final score results, providing reference opinions for enterprises to conduct digital transformation and a standardized reference for the entire industry. However, it is necessary to acknowledge this study's inherent limitations. The reliance on expert opinions and the relatively limited sample size for the questionnaire could introduce potential biases. Additionally, the intricate nature of the AHP-DEMATEL method may pose challenges when applied to more extensive datasets or diverse industry contexts. While this study has successfully addressed its research questions, certain nuances may remain unexplored, calling for further investigation into specific subdomains or variables within the context of digital transformation in construction enterprises.

From a practical standpoint, however, the developed evaluation model provides construction enterprises with a structured framework to navigate the complexities of digital transformation. By considering the critical factors unveiled by this study, construction companies can strategically align their digital initiatives with the unique realities of the construction industry, thus optimizing their digital transformation journey. In summary, this research contributes valuable insights to digital transformation within the construction industry. The findings emphasize the holistic nature of successful digital transformation, requiring the harmonization of technology, processes, and human capital. These insights inform the strategies and approaches of construction enterprises as they navigate the evolving landscape of digital innovation. Furthermore, due to the different business directions of construction enterprises, each company can formulate a trusted evaluation system to determine the digital maturity assessment model most suitable for its situation.

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