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Driving Factors behind the Adoption of Digital Twin Technology in Construction Enterprises

—Based on the Grounded Theory and Analytic Network Process

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Abstract

Under the development trend of digitalization and informatization of China's construction industry, the new generation of information technology represented by digital twin has shown great potential and development space in the deep integration with the construction industry. However, at present, the adoption of digital twin technology by construction enterprises is still very limited. Therefore, how to effectively promote the application and promotion of this technology in the construction industry is an urgent research problem to be solved. Based on the grounded theory, this paper takes domestic and foreign journal literature, government policies and industry reports, and interviews with construction enterprise personnel as research materials, and identifies 26 driving factors under six dimensions, such as technical level, technical advantage, and organizational management. Based on the survey results of 16 industry experts, the Analytic Network Process (ANP) method was used to determine the weight and ranking of each driving factor, and 10 key driving factors affecting the adoption of digital twin technology by construction enterprises were found. The research results show that the development of digital twin platform and related scientific research progress, government policy support and guidance, technical recognition and support of senior managers and other factors play an important role in the process of adopting digital twin technology in construction enterprises. To promote the application and development of digital twin technology, it is necessary to focus on the simultaneous improvement of key driving factors and implement reasonable and effective strategies.

Keywords

Digital Twin Technology, Construction Enterprises, Driving Factors, Grounded Theory, ANP

1. Introduction

Because of its ability to accurately simulate and verify the state and behavior of building physical entities, digital twin has some advantages such as significantly reducing operating costs and time, providing remote access, and promoting sustainability. It has become the core engine of the transformation and upgrading of the construction industry [1]. Manzoor Bilal *et al.* proposed that the application of digital twin technology in the construction industry can enhance visualization, promote information sharing, reduce construction pollution, increase production efficiency, and promote improvements in sustainability and safety [2]. Coupry Corentin believes that digital twins can realize the operation and maintenance of the whole life cycle of buildings [3]. In addition, digital twin also has technical advantages, such as reducing costs [4], improving efficiency [5], realizing automation and intelligent management of building operation and maintenance stage [6], and intelligent decision-making [4]. According to the white paper written by Ernst & Young's team, the application of digital twins will reduce the carbon emissions of buildings by 50%, increase the operation and maintenance efficiency by 35%, increase the productivity by 20%, and increase the space utilization rate by 15% [7]. Rubén Alonso *et al.* also further pointed out that the combination of digital twin technology and construction industry can reduce 15% of the energy in the operation and maintenance stage and accelerate 25% of the construction period in the construction stage [8]. Not only that, China's provinces have also introduced a series of policy measures to support the application of digital twins in the construction industry, such as promoting the construction of pilot cities and implementing pilot projects.

However, although digital twin technology has shown considerable technical advantages and application value in the field of architecture, it has also received strong support from government policies. However, as far as the current actual situation is concerned, digital twin technology is still in the early stage of technical discussion and preparation in the construction industry. There are few projects actually implemented, and the application and popularization of digital twin still has a long way to go. According to Gartner's radar chart of emerging technology impact published in 2022, digital twin technology is expected to take at least 3 - 6 years to reach the early adoption stage [9], and this process may take longer in the construction industry. In terms of reasons, on the one hand, because China's construction industry has always been regarded as one of the industries with the lowest degree of digitization, especially in the adoption of innovative technologies, the adoption of new technologies is restricted by the complexity of technology, the knowledge level of personnel, the conservatism of construction enterprises and other factors [10]. On the other hand, current practitioners in the construction industry still lack in-depth understanding and understanding of how digital twin technology can be better integrated with the construction industry. Therefore, in order to enhance its understanding, it is necessary to study the driving factors of digital twin technology adopted by construction enterprises, identify the direction and take effective measures to accelerate the further integration of digital twin technology and construction industry.

2. Identification of Driving Factors for Construction Enterprises to Adopt Digital Twin Technology Based on Grounded Theory

2.1. Data Sources and Collection

Because the development of digital twin in the construction industry has just started at this stage, the construction enterprise personnel have limited knowledge of this technology. Therefore, in addition to interviews with 27 relevant practitioners of construction enterprises, this study also combines a large number of relevant domestic and foreign literature and some government policies and industry reports in the process of data collection. The data from these three sources complement and verify each other, which not only ensures the comprehensiveness and accuracy of the extraction of driving factors, but also ensures that the driving factor system constructed in this study is in line with the actual situation of China's construction enterprises, making the research results more practical.

1) The collection and collation of journal literature is based on keyword searches in CNKI and Web of Science databases, such as "Digital Twin", "Architecture", "DT" and "Construction". By browsing the title and abstract of the literature, eliminating duplicate literature, radiation reading and full-text reading, 128 journal articles related to this research problem were retained as the initial data of grounded theory research, including 45 Chinese articles and 83 English articles.

2) Government policies and industry reports are obtained by searching relevant websites. A total of 10 research materials were included, including the "14th Five-Year Plan for Digital Economy Development" (Guo Fa No. 29), the "14th Five-Year Plan for Construction Industry Development" (Jian Shi No.11), the official website of Guanglianda Company: "Digital Twins and Lean Construction Deep Integration Boosts the High-quality Development of the Construction Industry," PwC Report (2020): "Digital Twins in Smart Cities," IDC Report (2023): "China's Smart City Digital Twin Technology Assessment" and so on.

3) In order to ensure the effectiveness of the interview data collection, first of all, the successful cases and project data are obtained through the official websites of many domestic digital twin technology software development companies, so as to determine the construction enterprises with strong representativeness as the research objects. Secondly, the interview outline is designed and pre-surveyed based on actual project cases, and the interview questions are further improved to ensure the validity of the outline. From May to July, the author interviewed 27 relevant personnel of construction enterprises. The interview time was about 40 minutes. The main interview questions included the adoption plan and adoption of digital twin technology, and the driving factors of adopting the technology. In addition, it is worth noting that the construction enterprises studied in this paper refer to all kinds of enterprises participating in engineering construction, management

and digital application in the whole industrial chain of the construction industry (Table 1).

Table 1. Descriptive statistics of interviewees.

Essential information	Class indication	Number	Percentage
Sexuality	Males	17	62.96%
	Female	10	37.04%
Age	Under 30 years old	6	22.22%
	30 - 40 years old	12	44.44%
	40 - 50 years old	7	25.93%
	Over 50 years old	2	7.41%
Job type	General manager	1	3.70%
	Project manager	3	11.11%
	Head of technical information department	2	7.41%
	Technical research and development personnel	2	7.41%
	Specialized technical personnel	4	14.81%
	Digital Technology Marketing Service Personnel	2	7.41%
	Other department heads and department personnel	13	48.15%
Working years	Less than 5 years	7	25.93%
	5 - 10 years	16	59.26%
	Over 10 years	4	14.81%
Interview form	Offline face-to-face interviews	19	70.37%
	Online Interviews	8	29.63%

2.2. Data Processing

According to the data processing flow of grounded theory three-level coding, through open coding, spindle coding and selective coding [11], the initial category is mined and the organic relationship between each category is identified. In order to further improve the transparency and traceability of grounded theory research and ensure the scientific and accurate analysis of data, the qualitative analysis tool Nvivo14 software was used to select 4/5 initial data for coding. In the coding process, following the idea of continuous comparison, experts are invited to jointly check and further discuss after each round of coding, so as to determine the final coding results and effectively guarantee the reliability and validity of the research. By creating free nodes and tree nodes in the software, the final refinement is identified 26 key initial categories, including core technologies of digital twins, development of digital twin platforms and related research advancements, digital twin fidelity, cross-network data security and privacy, and technical compatibility and further categorized them into six main dimensions: technological level factors, technical advantage factors, organizational management factors, economic environment factors, policy environment factors, and market environment factors. Through selective coding, the "driving factors for construction enterprises to adopt digital twin technology" were identified as the core category, and a narrative framework was constructed based on this core category, along with its main and subcategories (Table 2).

Table 2. Rooted theory coding results.

Main axis code (main category)	Open encoding (subcategory)
A1 Technical Level Factor	D1 Key Technologies of Digital Twins
	D2 Development of Digital Twin Platforms and Relevant Scientific Research Advances
	D3 The Fidelity of Digital Twins
	D4 Cross-network data security and privacy
	D5 Technical Compatibility
A2 Technical Advantage Factors	D6 Continuously improve products and services
	D7 Supports intelligent perception and simulation prediction
	D8 Real-time Data Analysis and Remote Control
	D9 Effective Information Sharing and Collaboration
	D10 Self-learning and optimization capabilities
	D11 Enhanced Visualization
	D12 Enhance Sustainability
	D13 Improve construction quality and efficiency
	D14 Supports the decision-making process
	D15 Facilitates the management of building safety risks
	D16 Contributes to environmental and energy management
	D17 Integration and Management of the Full Life Cycle of Buildings
A3 Organizational Management Factors	D18 Training of professionals in digital twin technology
	D19 Strategic Planning for Digital Twin Implementation by Construction Enterprises
	D20 Technical Recognition and Support from Senior Management
A4 Economic and Environmental Factors	D21 Improves corporate cost-effectiveness
	D22 Financial Investment and Effective Asset Management
A5 Policy and Environmental Factors	D23 Government policy support and guidance
A6 Market Environmental Factors	D24 Customer Satisfaction
	D25 Interest Perception and Sharing Among Stakeholders
	D26 Competitive Environment in the Construction Industry

2.3. Theoretical Saturation Test

Theoretical saturation test is a key step in grounded theory analysis. In the process of data analysis, saturation is usually judged based on whether there is a new code, that is, when no new code appears by adding additional data, it can be regarded as reaching saturation [12]. According to this test method, the 1/5 sample data reserved before (including 26 journal literature, 2 industry report data and 5 interview data) are encoded by repeating the above steps again, and compared with the existing analysis results. It is found that the categories extracted by the new round of coding can be included in the existing categories, and no new categories or main categories are found.

3. Importance Evaluation of Driving Factors for ANP-Based Digital Twin Technology Adoption in Construction Enterprises

3.1. Correlation Analysis of Driving Factors

ANP method is a super matrix based on feedback system, so the analysis of the correlation between the driving factors is the first step in the construction of ANP model. The research collects data through expert questionnaires, and invites a total of 16 experts with rich professional knowledge and industry practical experience in the field of digital transformation and digital twin technology research in the construction industry. The correlation between the above 26 driving indicators is judged and expressed by 0 - 1 points (influence = 1, no influence = 0). Because the evaluation of index relationship involves more professional knowledge, in addition to inviting experts from construction enterprises, experts are also invited from universities and technology research and development enterprises. Most of these experts are involved in the research field of digital transformation and digital twin technology in the construction industry, and have certain industry practical experience, which can make better feedback on the research content of this study.

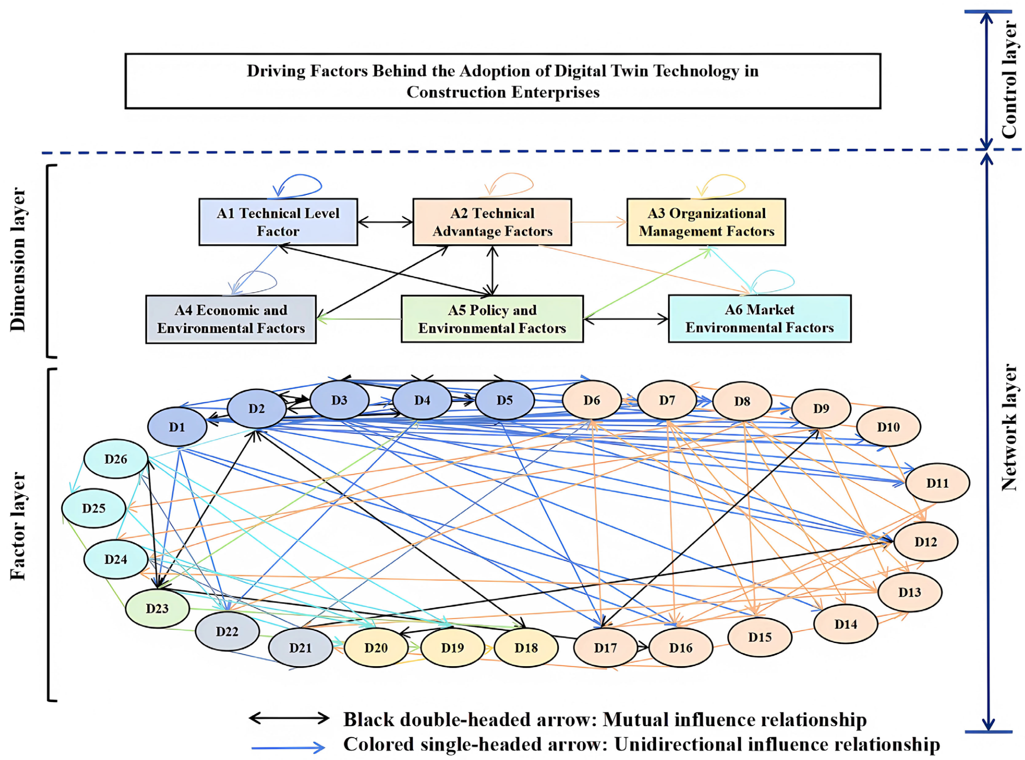

Figure 1. Structural diagram of the ANP network.

The final results of the recovered questionnaires were calculated by geometric mean, and the threshold value was set to 0.5 when the index relationship was determined. The mean value ≥ 0.5 was judged to be related (establishing ANP connection), and the mean value < 0.5 was judged to be unrelated (not establishing connection). The correlation results of the driving factors are shown in **Figure 1**.

3.2. Construction of the ANP Model and Weight Calculation

Enter the correlation results of each driving factor shown in **Figure 1** into the Super Decision software to construct an ANP network model of the driving factors for construction enterprises adopting digital twin technology. After model construction, pairwise importance comparisons must be conducted among interconnected driving factors to calculate their weight values, ultimately forming a judgment matrix. The research determines the relative importance of each driving factor through the 1 - 9 scale method, and assigns the importance of the index by forming an expert evaluation team. The experts are invited from the relevant personnel who have carried out the correlation evaluation of the driving index in the previous round. Because there are many judgment matrices involved in this stage and the scoring process is more complicated, in order to improve the efficiency of data collection, this study formed an expert evaluation group of 10 people. The scoring results were judged according to the group discussion. After the final discussion, the consensus was retained as the data source to construct the judgment matrix. Then, the normalized weight of the judgment matrix is solved by Super Decision software and the consistency test is carried out. The test standard is the CR value of each judgment matrix. If the CR value is less than 0.1, it passes the consistency test. For the judgment matrix that does not pass the consistency test, it is re-discussed by the expert group until it passes the test.

For example, by comparing the factors influencing D1 within the A2 technical advantage factor group under the sub-criteria of D1's core digital twin technologies, the resulting judgment matrix is presented in **Table 3**.

Table 3. Example of a judgment matrix.

D1 Key Technologies of Digital Twins	D7	D8	D9	D10	D11	D15	D16	Weight	CR
D7 supports intelligent perception and simulation prediction	1	1/3	3	1/2	2	2	2	0.1508	
D8 Real-time Data Analysis and Remote Control	3	1	4	1/2	3	2	2	0.2408	
D9 Effective Information Sharing and Collaboration	1/3	1/4	1	1/4	1/2	2	2	0.0781	
D10 Self-learning and optimization capabilities	2	2	4	1	1	3	4	0.2595	0.0661
D11 Enhanced Visualization	1/2	1/3	2	1	1	2	3	0.1378	
D15 facilitates the management of building safety risks	1/2	1/2	1/2	1/3	1/2	1	1	0.0694	
D16 contributes to environmental and energy management	1/2	1/2	1/2	1/4	1/3	1	1	0.0635	

The core work of ANP network analysis is to solve the super matrix, including solving the unweighted super matrix, the weighted super matrix and the limit super matrix. The judgment data is input into the Super decision software, and the super matrix is convergent. Finally, the weight and ranking results of each driving factor are obtained as shown in Figure 2.

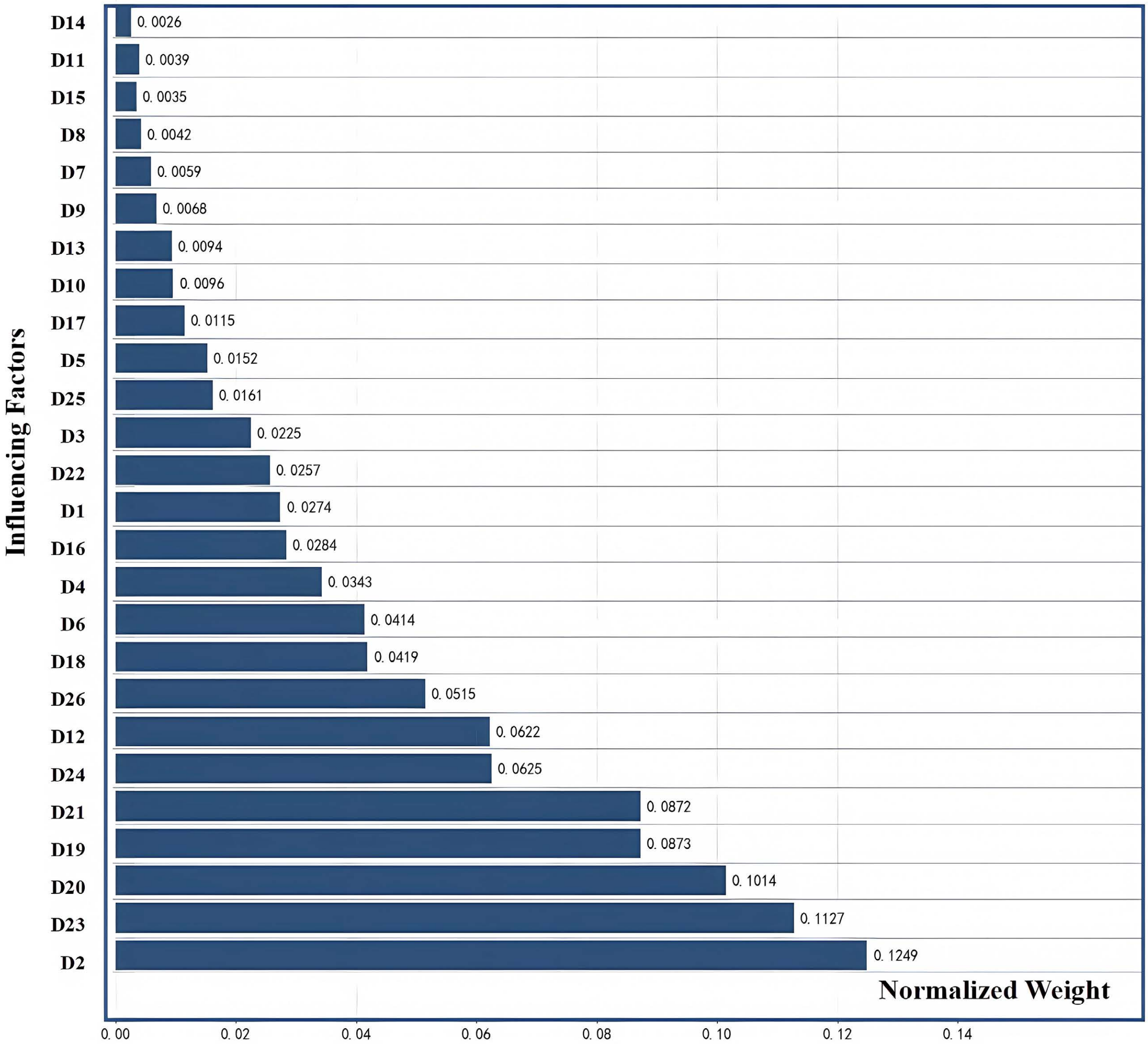

Figure 2. Weight distribution results and comprehensive ranking of key performance indicators for construction enterprises adopting digital twin technology.

3.3. Result Analysis

Based on ANP network analysis method, the importance of driving factors for construction enterprises to adopt digital twin technology is quantitatively evaluated. It is found that the development of D2 digital twin platform and related scientific research progress are the most important factors to promote the technology adoption of construction enterprises. This is because the application of digital twin technology mainly relies on digital twin platform. The progress of related scientific research and the development of digital twin platform for construction enterprises have promoted the progress of technology and improved the usefulness and ease of use of technology. The second is the policy support and guidance of the D23 government, which ranks second and has a high weight. This also fully shows that the policy environment factor is not unimportant. On the contrary, government policies play an important leading and guiding role in the adoption of digital twin technology by construction enterprises. The three driving factors in the group of organizational management factors are all included in the scope of particularly important factors, ranking ninth, fourth and third respectively, which once again confirms that construction enterprises are the main body of digital twin technology adoption. The training of D18 digital twin technology professionals, the strategic planning of D19 construction enterprises for digital twin implementation, and the technical recognition and support of D20 senior managers all play an important role in the process of technology adoption. The driving factor of D21 "improve the cost-effectiveness of enterprises" ranks fifth, which is consistent with the actual situation. Cost control is the key to the survival and development of construction enterprises. Whether the adoption of new technologies can bring significant cost-effectiveness directly affects the profitability and return on investment of the project. D24 customer satisfaction ranks sixth, which corresponds to the driving factor of D6 "continuous improvement of products and services" ranked tenth, is also a key factor that enterprises need to consider when adopting digital twin technology. The importance of the driving factor of D12 improving sustainability is ranked seventh, and this factor ranks first among all the driving factors of technical superiority, which reflects the long-term pursuit of construction enterprises in saving resources and improving efficiency, further improving economic, environmental and social benefits, and realizing sustainable development. In addition, China's construction enterprises are usually market-oriented, which means that the business decision-making and business development of enterprises are based on market demand. Therefore, the market competition environment of D26 construction industry has also become a particularly important driving factor for construction enterprises to adopt digital twin technology, ranking eighth. The weights of the above 10 factors are all above 0.038, which are all greater than the average weight level. Therefore, they are regarded as the key driving factors, and the future is the key direction that construction enterprises need to pay attention to when adopting digital twin technology.

4. Implementation Strategies to Promote the Adoption of Digital Twin Technology by Construction Enterprises

Based on the above analysis, in order to effectively improve the key driving factors and promote the application of digital twin in the construction industry, the following aspects should be considered:

1) From the perspective of technology R&D enterprises, they should establish contact with construction enterprises and develop customized digital twin platforms for them. The development of the platform should be based on the needs of

construction enterprises for interface design and functional configuration, and has good scalability and can be compatible with the hardware and software systems of construction enterprises. In addition, they should also actively participate in the establishment of industry standards for digital twin technology. Unified industry standards enable different enterprises to follow certain norms and processes in the application of digital twins, and further improve the standardization of digital twin platforms. Finally, they should actively cooperate with scientific research institutions and universities to promote the development and innovation of digital twin technology and further improve the popularity of technology by sharing knowledge, experience and practical cases.

2) From the perspective of government, government departments need to introduce special policies to promote the innovative application of digital twin technology in construction enterprises. For example, financial subsidies should be given to construction companies to purchase hardware and software equipment needed for digital twins, technical guidelines should be provided for construction companies, etc, and data privacy protection and security requirements should be clarified. Establish an information sharing platform for digital twin technology, provide online forums, technical resource libraries, seminars and other forms of communication and learning methods, and promote technical exchange activities in the construction industry. Before the full deployment of the digital twin, they should take the lead in carrying out pilot projects, and appoint a professional team to track the projects in real time, and form a reporting guide for the implementation cases and data experience of the demonstration projects, so that construction enterprises can refer to and learn from them.

3) From the perspective of construction enterprises, before adopting digital twins, enterprises should formulate clear goals and key performance, such as maximizing energy efficiency and improving project management. The top managers of construction enterprises need to strengthen the cognition of digital twin, fully understand the application advantages of this technology and the core competitiveness that can be brought to enterprises by adopting this technology. They should actively formulate training and development plans within the organization to ensure that employees in the enterprise have the knowledge and skills needed to apply digital twins. At the same time, they should actively establish cooperation with universities, scientific research institutions and industry associations to obtain the latest technical knowledge and industry trends.

5. Conclusion

The results of this study will help to enhance the understanding and recognition of digital twin technology in construction enterprises, help enterprise managers to formulate more scientific technology adoption plans and strategic decisions, and also provide reference for government departments, technology research and development enterprises and other parties to jointly promote the application and promotion of digital twin technology in the construction industry. However, constrained by the nascent development of digital twin technology in China's construction industry, it is challenging to collect substantial objective data. Consequently, both the identification of driving factors for building enterprises to adopt digital twin technology and their importance assessment rely on qualitative research methods. In future research, questionnaire survey can be used to collect large sample data, so as to obtain more objective and accurate results.

Conflicts of Interest

The author declares no conflict of interest in this study.

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