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Analysis of the Drivers of Highway Construction Companies Adopting Smart Construction Technology

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Abstract: In this study, we aimed to identify the influencing factors that drive highway construction companies to adopt smart construction technologies. Using expert interviews and expert scoring, we collected interview data from 25 experts in the field and we proposed the TOSE framework based on the TOE framework, identifying four dimensions and fourteen influencing factors. We analyzed the results using the Fuzzy DEMATEL-ISM method, and we then summarized the findings according to the evaluation criteria to determine the validity of the fourteen hypotheses and the extent to which they drive highway construction companies to adopt smart construction technologies. The findings of this paper are of high value to decision makers and participants in highway construction companies, as well as to other companies in the construction industry, in their decision to adopt smart construction technologies.

Keywords: decision making; Fuzzy DEMATEL–ISM; highway construction companies; driving influences; smart construction technology

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1. Introduction

By the end of 2020, the total mileage of roads in China exceeded 5.19 million kilometers, of which 161,000 km belonged to highways, ranking first in the world. However, with the progress of technology, smart construction has gradually replaced traditional construction methods with its advantages of high efficiency, low energy consumption, low loss, and low pollution. Most smart construction technologies are new, so many domestic highway construction companies still maintain an observant and hesitant attitude. Because the construction of highways involves long construction periods, large land areas, and environmental pollution, damage to the environment, and a waste of resources, in the long run, will be serious and irreversible, which is contrary to the concept of sustainable development in China [1]. Therefore, the integration of multidisciplinary knowledge and the development of smart construction technology are issues that cannot be ignored by highway construction companies in China [2].

In recent years, as an emerging technology, intelligent construction technology has attracted the attention of many experts and scholars. Gyamfi et al. delved into the current state of the construction industry in Ghana and found that most construction professionals failed to recognize the concept of smart construction [3]. Luo et al. conducted a comprehensive review of state-of-the-art intelligent control systems for energy and comfort management in sustainable and intelligent construction buildings [4]. Lv and others apply big data technologies that combine autoencoders as building blocks to apply deep architecture models to represent traffic flow characteristics for prediction [5]. Taking China's smart city pilot policy as a starting point, Guo et al. used the asymptotic difference method to systematically evaluate and to point out the importance of applying intelligent construction technology to build cities and new infrastructure construction [6]. Li et al. summarized the blockchain technology in the construction industry, and proposed an implementation framework and conceptual model to solve the problem of conceptual understanding and knowledge structure expansion [7]. Sun et al. summarized the drone technology in intelligent construction technology, and introduced the application of UAVs for urban planning, illegal construction supervision, engineering environmental management, waste management, intelligent transportation, and other aspects [8]. He et al. applied constrained least squares to optimize intelligent video surveillance technology [9]. Arka et al. reviewed IoT technologies in smart construction technologies, analyzing key drivers and research trends [10].

The scholars of the above research analyzed the adoption factors and application statuses of smart construction technology from various angles, but research on the factors that drive highway construction companies to adopt smart construction technology is scarce, which may also be a reason for the low level of smart highway construction in China. Therefore, this paper aims to identify the factors that drive Chinese highway construction companies to adopt smart construction technology and to determine the role of these factors in the adoption of smart construction technology by companies, thus promoting the use of smart construction technology by highway construction companies and filling the research gap in this field.

2. Theoretical Foundations

The Technology–Organization–Environment (TOE) framework theory was first proposed by Tornatzky in the 1990s [11]. The theory consists of three dimensions: the technological dimension, the organizational dimension, and the environmental dimension. In recent years, the TOE framework theory has been applied to numerous smart construction technology adoption studies, including BIM technology, cloud computing technology [12], big data technology [13], Internet of Things technology [14], blockchain technology [15], etc. For example, Badi et al. (2021) applied the TOE framework to conduct an empirical study on the determinants of smart contract adoption in the construction industry from the perspective of UK contractors [16]. Based on the TOE framework, Kim et al. (2021) proposed variables that influence the adoption of blockchain technology and found that blockchain technology has a positive impact on logistics performance [17]. Ullah et al. proposed a multi-layered risk management framework based on the TOE framework to identify and manage the risks associated with smart city governance [18]. The technological dimension mainly covers the internal and external dimensions of technology, such as the existing technology of a company and the cost of adopting new technology. The organizational dimension includes management-related structures, such as top-management support and corporate culture, and the environmental dimension involves the external environment in which the company operates, such as the competitive peer environment and the policy environment of the company's location [19].

The research object of this paper is the identification of the drivers of adopting smart construction technology by highway construction companies, and the TOE framework theory is utilized from a more organizational perspective and is more widely applied. In this paper, we adopt Fuzzy DEMATEL–ISM for model construction to analyze the influencing factors. The TOE framework theory can provide a more comprehensive framework regarding the potential factors, so we chose the TOE framework for its theoretical perspective [20,21]. Given that the subject of this paper is a highway construction company with a wide range of technologies, a large organizational system, and a complex environment, the adoption of smart construction technologies is not limited to the technical, organizational, and environmental dimensions. Thus, in conjunction with the TOSE framework (i.e., Technical, Organizational, Social, and Environmental Resilience) proposed by Bruneau to explain resilient cities, after discussing with various experts and scholars, we added the social dimension and its influencing factors to the TOE framework theory [22].

Based on a literature search and expert feedback, in this section, we identify and determine the main factors that influence Chinese highway construction companies to adopt smart construction technologies. We conducted the literature search in May 2022, and we selected the Web of Science database. We did not set a time limit, as research related to smart construction technologies and their adoption is an emerging topic. The searched keywords included "Smart build and adopt", "Smart build and Influencing factors", "Willingness to adopt smart building technologies", and "Build and adopt". To improve the quality of the study and identify all possible factors influencing highway construction companies' decisions to adopt intelligent building technology, this paper sets up a filter such that only English journal literature is retained. The preliminary search of Web of Science totaled 1802 articles, and we then eliminated 575 duplicates; browsed the title, abstract, and keywords of the literature to remove 916 irrelevant studies; eliminated 277 studies through full-text reading; and finally screened and retained 34 studies on the possible driving factors for the adoption of intelligent construction technology by expressway construction enterprises in China. The process is shown in Figure 1. The identified influencing factors are shown in Table 1.

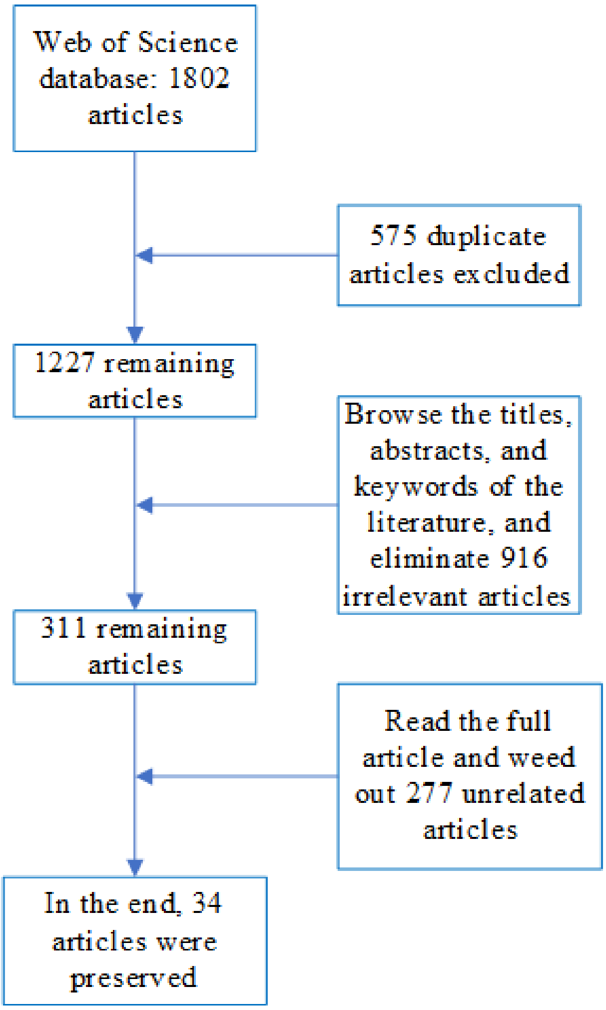

Figure 1. Literature-selection process.

Table 1. Identified influencing factors.

No.	Influencing Factors	References
1	Technical advantages	[23–31]
2	Technical costs	[24,27,32–34]
3	Complexity	[23,27,29,35–37]
4	Compatibility	[23,28,35,36,38]
5	Corporate Culture	[33,39]
6	Resource Readiness	[24,26,34,39]
7	Senior management support	[24,26,32,39–42]
8	Staff Support	[26,32,34,41]
9	Competitive market pressures	[24,26,33]
10	Policy environment	[16,35,36,43,44]
11	Economic environment	[24,27,45,46]
12	Stakeholder engagement	[16,24,28,33,34,36]
13	Corporate Social Responsibility	[16,40]
14	Sustainable development	[36,37,45–48]
15	Company size	[23]
16	Professional training	[24]
17	Security	[25]

3. Identification and Hypotheses of Influencing Factors

Combined with the influencing factors in Table 1, the authors discussed with 25 experts and scholars on “Drivers of Highway Construction Companies Adopting Smart Construction Technology”. Finally, three influencing factors were removed, and 14 driving factors were retained and divided into four dimensions for analysis and hypothesizing.

3.1. Identification of Influencing Factors in the Technological Dimension

Compared with traditional construction technology, smart construction technology has the advantages of high efficiency, low energy consumption, low pollution, etc. Mastering and applying smart construction technology can bring long-term benefits and sustainable development to highway construction companies. The adoption of smart construction technology requires not only purchasing new equipment but also investing in training for technicians, the maintenance of equipment, and hiring experts. The application of smart construction technology can achieve unified management that can progress highway construction projects by sharing engineering construction data on the system platform while improving the speed of information transfer and enhancing the privacy of information storage. However, the complexity and risks involved in implementing smart construction technology require careful planning and management [24,25,35]. The application of smart construction technology will inevitably conflict with the application of original technology, which includes not only software and data compatibility but also hindrances in the management process of highway construction. However, whether this compatibility issue will hinder the adoption of smart construction technology by highway construction companies needs to be further explored [49,50].

3.2. Hypotheses of the Influencing Factors in the Technological Dimension

These assumptions include factors such as “technological advantage”, “technological cost”, “complexity”, and “compatibility”. Therefore, we propose the following hypotheses in this study.

H1a: *Better technological advantages have a significant positive effect on driving highway construction companies to adopt smart construction technologies.*

H1b: *Lower technology costs have a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

H1c: *Lower complexity has a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

H1d: *Good compatibility has a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

3.3. Identification of Influencing Factors in the Organizational Dimension

A company with a solid, conservative mindset often lags behind or even refuses to adopt new technologies, whereas a company with an innovative mindset is always ahead of current planning trends regarding adopting new technologies. Thus, corporate culture is also an important influencing factor in determining the adoption of smart construction technology by highway construction companies [51,52]. Adequate reserves of talent, capital, technology, and other resources can enable highway construction companies to integrate and apply smart construction technology more quickly and steadily, whereas companies with a lack of or insufficient resources may have certain obstacles and difficulties in adopting smart construction technology [26]. Top management support for smart construction technologies can stimulate employee potential, improve productivity, and make them feel trusted and more focused on their work. Moreover, top management stimulates change by communicating and reinforcing company values, thus influencing the adoption of new technologies [23,41,42,53]. The attitudes of technical professionals towards the adoption of new technologies are important, including software technicians in the design and planning phase, equipment technicians in the construction and maintenance phase, etc. Their ability to coordinate and collaborate with experts and academics influences the adoption of smart construction technologies. The adoption of smart construction technologies by highway construction companies requires training existing staff in the operation of new software or equipment or recruiting specialist technicians, which not only increases the size of the company to a small extent but also improves its core competitiveness [23,31,32].

3.4. Hypotheses of the Influencing Factors in the Organizational Dimension

These factors include “corporate culture”, “resource readiness”, “top management support”, and “employee support”. Therefore, we propose the following hypotheses in this study.

H2a: *Better corporate culture has a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

H2b: *Better resource readiness has a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

H2c: *Top management support has a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

H2d: *Employee support has a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

3.5. Identification of Influencing Factors in the Environmental Dimension

Influencing factors in the environmental dimension are mainly divided into competitive market pressure, policy environment, and economic environment. Among these, competitive market pressure refers to the pressure felt by companies when competitors in the same industry adopt or prepare to apply new technologies, and it is an inevitable product of competition in the industry. When this competitive pressure arises, companies may apply innovations in the industry, which, in turn, reduce competitive market pressure and change the competitive market environment [16,54,55]. Policy environment refers to mandatory policies or recommendations related to smart construction in the locality or country where the company is located. Government incentives, subsidies, and support for new technology can have a significant impact on the adoption and diffusion of new technology by companies [13]. The economic environment includes pressure from customers and pressure from partners. For example, if smart construction technology is recognized by customers or applied by partners, to ensure meeting its technical concept and goals, the company is likely to use it to better communicate and cooperate or to meet customer needs [56]. To apply smart construction technologies for highway construction, highway construction companies need to collaborate with external parties, where stakeholder involvement and support play an important role. Making stakeholders aware of and familiar with smart construction technologies and then mastering and using these technologies is an important influencing factor for the adoption of smart construction technologies [57].

3.6. Hypotheses of the Influencing Factors in the Environmental Dimension

These factors include "competitive market pressure", "policy environment", "economic environment", and "stakeholder involvement". Therefore, we propose the following hypotheses in this study.

H3a: *Competitive market pressure has a significant positive effect on driving highway construction companies to adopt smart construction technologies.*

H3b: *A good policy environment has a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

H3c: *A good economic environment has a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

H3d: *Stakeholder involvement has a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

3.7. Identification of Influencing Factors in the Social Dimension

Due to strict site selection, long construction periods, high costs, large investments, and large scales in construction, highway construction companies are required to strictly comply with laws, regulations, industry standards, and other institutional requirements during the design and construction stages. As a result, companies with a better sense of social responsibility are more likely to give preference to the application of smart construction technologies to ensure that the highway schedule is not delayed, that the project quality is high, and that people are better served [58,59]. Sustainable development refers to meeting the needs of the present generation for economic, environmental, and social development without preventing future generations from meeting their needs [60]. The adoption and application of smart construction technologies can help companies to transform and innovate [61].

3.8. Hypotheses of the Influencing Factors in the Social Dimension

These factors include "corporate social responsibility" and "sustainable development", and therefore, we propose the following hypotheses in this study.

H4a: *Better corporate social responsibility has a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

H4b: *Sustainable development has a significant positive impact on driving highway construction companies to adopt smart construction technologies.*

In summary, after discussing with industry experts and scholars, to analyze the mechanism of the impact of driving highway construction companies to adopt smart construction technology, we propose a framework for analyzing the drivers of smart construction technology adoption by highway construction companies based on the TOE framework theory, including 14 key drivers in four dimensions: technology, organization, environment, and society, as shown in Table 2.

Table 2. Summary of drivers for the adoption of smart construction technology by China's highway construction companies.

Main Factors	No.	Sub-Factors	Description of Influencing Factors
Technological dimension	H1a	Technical advantages	The influencing factors of the technological dimension influence the adoption of smart construction technology by motorway construction companies. The smart construction of motorways is achieved through the capture, collection, integration, and analysis of information.
	H1b	Technical costs	
	H1c	Complexity	
	H1d	Compatibility	
Organizational dimension	H2a	Corporate Culture	The influencing factors of the organizational dimension influence acceptance and support at various levels within an organization when adopting smart construction technologies.
	H2b	Resource Readiness	
	H2c	Senior management support	
	H2d	Staff Support	
Environmental dimension	H3a	Competitive market pressure	The influencing factors of the environmental dimension affect collaboration between companies and external parties, which, in turn, support and help each other to adopt smart construction technologies.
	H3b	Policy environment	
	H3c	Economic environment	
	H3d	Stakeholder engagement	
Social dimension	H4a	Corporate social responsibility	The influencing factors of the social dimension affect the transformation of corporate strategies and behaviors under the constraints of the social dimension.
	H4b	Sustainable development	

Through the above analysis, we established a system of drivers for the adoption of smart construction technology by China's highway construction companies, as shown in Figure 2.

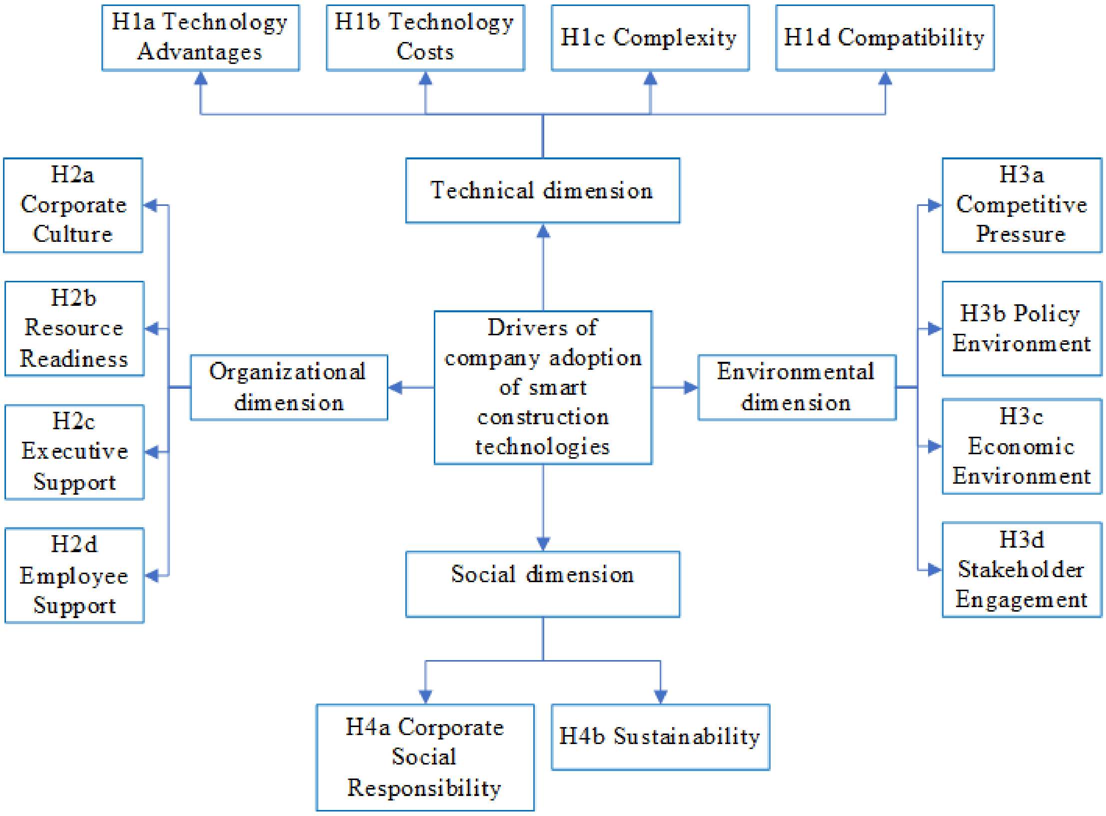

Figure 2. System of influences driving the adoption of smart construction technology by highway construction companies in China.

4. Research Methods and Processes

We applied the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method of analysis. This method makes full use of expert knowledge and experience to identify and analyze complex factor networks and to explore causal relationships between factors by establishing relationship matrices through matrix and graph theory [62]. However, this method is too subjective, expert judgments vary greatly, and the research results are somewhat biased. Therefore, we combined the triangular fuzzy numbers in fuzzy set theory with DEMATEL to form the Fuzzy DEMATEL method. This method fuzzifies the direct influence matrix by transforming expert semantics into corresponding triangular fuzzy numbers, and the CFCS method is later applied to defuzzify and to further process and clarify hierarchical relationships [63].

We established a system of driving influences and conducted research using expert interviews and expert scoring. We contacted 35 experts with relevant experience in this research effort, and we eventually obtained the support of 25 experts after consultation. These experts were from leading construction companies, research institutes, and universities. We based the research on a scale scoring principle, and the average conversation time was 15 min. The specific background information of the experts is shown in Table 3. After collating the experts' scores, we conducted reliability and validity analyses, and the results are shown in Table 4. The Cronbach's alpha coefficient of 0.870 was greater than 0.8 and the KMO value, and the Cronbach's alpha of 0.823 was greater than 0.7, fully demonstrating the validity of the questionnaire. The blank scoring questionnaire is shown in Supplementary Materials, and the selection of the influencing factors in the table is the conclusion of discussion with experts and scholars, and minor changes are still required if applied to other fields.

Table 3. Background information of experts.

Features	Features	Number of People
Educational background	Undergraduate	1
	Masters	9
	PhD	15
Relevant work experience	5–10 years	6
	10–15 years	6
	More than 15 years	13
Work Unit	Constructor	5
	Designer	9
	Higher education institutions	11
Jobs	Technical positions	6
	Management positions	8
	Technical + management positions	11
Title	Intermediate title	8
	Senior title	17

Table 4. KMO and Bartlett's test.

Projects		Test Value
KMO	Metrics	0.823
Bartlett's test for sphericity	Approximate cardinality	992.052
	Df	270
	Sig.	0

The specific process of trigonometric fuzzy number transformation is as follows.

1. Based on the construction of the driver indicators, we constructed an expert semantic scale. We classified the influencing factors into five levels: no influence, "0"; weak influence, "1"; average influence, "2"; strong influence, "3"; and strong influence, "4".

2. Based on the scoring results of each expert, we constructed an initial matrix of order n: $C = |cij|n \times n$. c_{ij} means the degree of influence of factor F_i on factor F_j.
3. We transformed the initial direct influence matrix into a triangular fuzzy number, which is expressed as $X = (l, m, r)$, where l is the left-hand side value, i.e., the conservative value; m is the middle value, i.e., the closest to the actual value; and n is the right-hand side value, i.e., the optimistic value, satisfying both $X_{ij}^{k} = \left(l_{ij}^{k}, m_{ij}^{k}, n_{ij}^{k}\right)$, as shown in Table 5. We intended the final result to be the degree to which the kth expert believed that factor i influences factor j.

Table 5. Semantic conversion table.

Semantic Variables	Triangular Fuzzy Number
No impact	(0,0,0.25)
Weaker impact	(0,0.25,0.5)
General Impact	(0.25,0.5,0.75)
Stronger impact	(0.5,0.75,1)
Strong Impact	(0.75,1,1)

We applied the CFCS method for defuzzification to obtain the direct influence matrix Z. The process is as follows.

1. Normalization of the triangular fuzzy number $ls_{ij}^{k} = (l_{ij}^{k} - \min l_{ij}^{k})/\Delta_{\min}^{\max}$:

$$ms_{ij}^{k} = (m_{ij}^{k} - \min l_{ij}^{k})/\Delta_{\min}^{\max}$$

$$rs_{ij}^{k} = (r_{ij}^{k} - \min l_{ij}^{k})/\Delta_{\min}^{\max}$$

$$\Delta_{\min}^{\max} = \max r_{ij}^{k} - \min l_{ij}^{k}$$

ls_{ij}^{k}, ms_{ij}^{k}, and rs_{ij}^{k} are the normalized values of the left-hand side of the triangular fuzzy number l_{ij}^{k}, the middle value m_{ij}^{k}, and the right-hand side of the triangular fuzzy number r_{ij}^{k}, respectively. $\Delta_{\min}^{\max}$ is the difference between the right-hand side and the left-hand side.

2. Normalization of left-hand and right-hand values $u_{ij}^{k} = ms_{ij}^{k}/(1 + ms_{ij}^{k} - ls_{ij}^{k})$:

$$v_{ij}^{k} = rs_{ij}^{k}/(1 + rs_{ij}^{k} - ms_{ij}^{k})$$

u_{ij}^{k} and v_{ij}^{k} are the normalized values for the left-hand and right-hand values, respectively.

3. Calculating clear values:

$$z_{ij}^{k} = \min c_{ij}^{k} + \Delta_{\min}^{\max}\left[\min u_{ij}^{k}(1 - u_{ij}^{k}) + v_{ij}^{k} v_{ij}^{k}\right]/\left[1 - u_{ij}^{k} + v_{ij}^{k}\right]$$

4. Calculating the mean of the clear values to obtain the direct impact matrix: $z_{ij} = (z_{ij}^{1} + z_{ij}^{2} + \ldots + z_{ij}^{k})/k$

$$Z = |z_{ij}|_{n \times n}$$

By aggregating and collating the scoring results of the 15 experts and scholars, we transformed each scoring result into a triangular fuzzy number and later de-fuzzified it to obtain the direct impact matrix.

We standardized the direct impact matrix as follows, and we standardized the direct impact matrix as shown in Table 6.

$$\lambda = 1/\max_{1\leq i\leq n}\sum_{j=1}^{n} z_{ij}, G = \lambda Z$$

Table 6. Standardization of the direct impact matrix of factors driving the adoption of smart construction technologies by companies.

Factors	H1a	H1b	H1c	H1d	H2a	H2b	H2c	H2d	H3a	H3b	H3c	H3d	H4a	H4b
H1a	0	0.1021	0.0743	0.0625	0.0721	0.0650	0.0721	0.0490	0.0843	0.0879	0.0692	0.0505	0.0494	0.0944
H1b	0.0828	0	0.0728	0.0577	0.0460	0.0554	0.0734	0.0518	0.0806	0.0964	0.0921	0.0792	0.0720	0.0813
H1c	0.0841	0.0777	0	0.0754	0.0582	0.0797	0.0863	0.0741	0.0621	0.0762	0.0655	0.0799	0.0732	0.0835
H1d	0.0799	0.0748	0.0601	0	0.0706	0.0643	0.0863	0.0577	0.0598	0.0750	0.0741	0.0639	0.0864	0.0992
H2a	0.0565	0.0614	0.0637	0.0428	0	0.0702	0.0642	0.0724	0.0730	0.0774	0.0471	0.0628	0.0948	0.0963
H2b	0.0603	0.0645	0.0670	0.0594	0.0763	0	0.0652	0.0595	0.0734	0.0685	0.0850	0.0568	0.0850	0.0848
H2c	0.0837	0.0577	0.0798	0.0546	0.0821	0.0748	0	0.0697	0.0813	0.0742	0.0680	0.0570	0.0592	0.0770
H2d	0.0738	0.0747	0.0711	0.0766	0.0676	0.0754	0.0741	0	0.0543	0.0661	0.0628	0.0583	0.0826	0.0719
H3a	0.0708	0.0955	0.0748	0.0705	0.0666	0.0647	0.0683	0.0781	0	0.0973	0.0792	0.0676	0.0708	0.0732
H3b	0.0755	0.0552	0.0615	0.0755	0.0711	0.0863	0.0835	0.0528	0.0857	0	0.0811	0.0921	0.0992	0.0754
H3c	0.0748	0.0777	0.0528	0.0568	0.0459	0.0763	0.0670	0.0630	0.0679	0.0892	0	0.0736	0.0706	0.0550
H3d	0.0537	0.0777	0.0537	0.0542	0.0570	0.0835	0.0799	0.0550	0.0706	0.0752	0.0728	0	0.0764	0.0717
H4a	0.0633	0.0542	0.0437	0.0609	0.0704	0.0633	0.0805	0.0609	0.0473	0.0790	0.0884	0.0712	0	0.0906
H4b	0.0886	0.0944	0.0559	0.0672	0.0556	0.0732	0.0763	0.0690	0.0641	0.0878	0.0736	0.0692	0.0748	0

We calculated the combined impact matrix as follows, as shown in Table 7.

$$T = G(1 - G)^{-1}$$

The process for calculating the degree of influence and the degree of being influenced is as follows.

$$e_i = \sum_{i=1}^{n} t_{ij}, i = 1, 2, \ldots n$$

$$f_i = \sum_{j=1}^{n} t_{ij}, i = 1, 2, \ldots n$$

where t_{ij} is the influence value of element i on element j in the integrated image matrix T; f_i is the degree of influence of element i; and e_i is the degree of element i being influenced.

The degree of influence is the sum of the rows in which the factors are located and is the combined influence of the corresponding factor in that row on all other factors.

The influencedness is the sum of the columns in which each factor is located and is the combined influence of the factors in that column on all other factors.

Table 7. Composite impact matrix of influencing factors driving the adoption of smart construction technologies by companies.

Factors	**H1a**	**H1b**	**H1c**	**H1d**	**H2a**	**H2b**	**H2c**	H2d	H3a	H3b	H3c	H3d	H4a	H4b
H1a	0.8799	0.9866	0.8436	0.8195	0.8487	0.9241	0.9687	0.8045	0.9217	1.0548	0.9610	0.8722	0.9622	1.0515
H1b	0.9610	0.8983	0.8458	0.8199	0.8306	0.9215	0.9754	0.8108	0.9228	1.0674	0.9865	0.9020	0.9865	1.0450
H1c	0.9903	0.9986	0.8033	0.8597	0.8672	0.9701	1.0157	0.8548	0.9335	1.0802	0.9917	0.9281	1.0173	1.0791
H1d	0.9652	0.9740	0.8406	0.7704	0.8586	0.9353	0.9934	0.8219	0.9107	1.0558	0.9771	0.8940	1.0063	1.0691
H2a	0.8839	0.9008	0.7905	0.7604	0.7393	0.8815	0.9123	0.7835	0.8637	0.9908	0.8921	0.8369	0.9517	1.0002
H2b	0.9064	0.9232	0.8101	0.7911	0.8267	0.8345	0.9325	0.7886	0.8825	1.0046	0.9446	0.8495	0.9628	1.0109
H2c	0.9409	0.9323	0.8347	0.7993	0.8448	0.9181	0.8855	0.8097	0.9037	1.0249	0.9433	0.8624	0.9547	1.0199
H2d	0.9220	0.9354	0.8174	0.8093	0.8228	0.9080	0.9443	0.7349	0.8694	1.0059	0.9289	0.8538	0.9643	1.0046
H3a	0.9817	1.0168	0.8754	0.8582	0.8765	0.9600	1.0030	0.8608	0.8778	1.1023	1.0068	0.9211	1.0190	1.0729
H3b	1.0003	0.9975	0.8769	0.8753	0.8953	0.9943	1.0320	0.8526	0.9715	1.0346	1.0244	0.9562	1.0596	1.0924
H3c	0.8940	0.9092	0.7763	0.7674	0.7781	0.8811	0.9086	0.7690	0.8548	0.9949	0.8459	0.8409	0.9240	0.9573
H3d	0.8795	0.9127	0.7803	0.7681	0.7913	0.8910	0.9237	0.7660	0.8605	0.9870	0.9132	0.7759	0.9332	0.9761
H4a	0.8798	0.8841	0.7638	0.7667	0.7957	0.8658	0.9158	0.7640	0.8322	0.9809	0.9174	0.8345	0.8539	0.9834
H4b	0.9714	0.9899	0.8363	0.8327	0.8444	0.9418	0.9834	0.8302	0.9138	1.0657	0.9761	0.8978	0.9950	0.9767

The process for calculating centrality and causality is as follows.

$$\mathrm{M}_i = f_i + e_i, i = 1, 2, \ldots n$$

$$\mathrm{N}_i = f_i - e_i, i = 1, 2, \ldots n$$

Centrality is expressed as the position of the factor in the system and the strength of its influence and is the sum of the degree of influence and the degree of being influenced. The degree of cause is the difference between the degree of influence and the degree of being influenced, representing the causal relationship between influencing factors. If the degree of cause is greater than 0, it is the causal factor, and if it is less than 0, it is the effect factor. The degree of influence, degree of being influenced, degree of centrality, and degree of cause were calculated, as shown in Table 8. Accordingly, we made a causality diagram of the influencing factors, as shown in Figure 3.

Table 8. Indicators of the comprehensive impact matrix analysis of the factors driving the adoption of smart construction technologies by companies.

Projects	Degree of Impact	Degree of Being Influenced	Centrality	Degree of Cause
H1a	12.8990	13.0565	25.9555	−0.1575
H1b	12.9733	13.2595	26.2329	−0.2862
H1c	13.3896	11.4950	24.8846	1.8946
H1d	13.0722	11.2981	24.3702	1.7741
H2a	12.1876	11.6199	23.8075	0.5676
H2b	12.4678	12.8271	25.2950	−0.3593
H2c	12.6743	13.3943	26.0686	−0.7200
H2d	12.5210	11.2514	23.7724	1.2696
H3a	13.4321	12.5185	25.9507	0.9136
H3b	13.6629	14.4496	28.1124	−0.7867
H3c	12.1016	13.3089	25.4105	−1.2074
H3d	12.1586	12.2251	24.3838	−0.0665
H4a	12.0381	13.5905	25.6285	−1.5524
H4b	13.0553	14.3389	27.3942	−1.2837

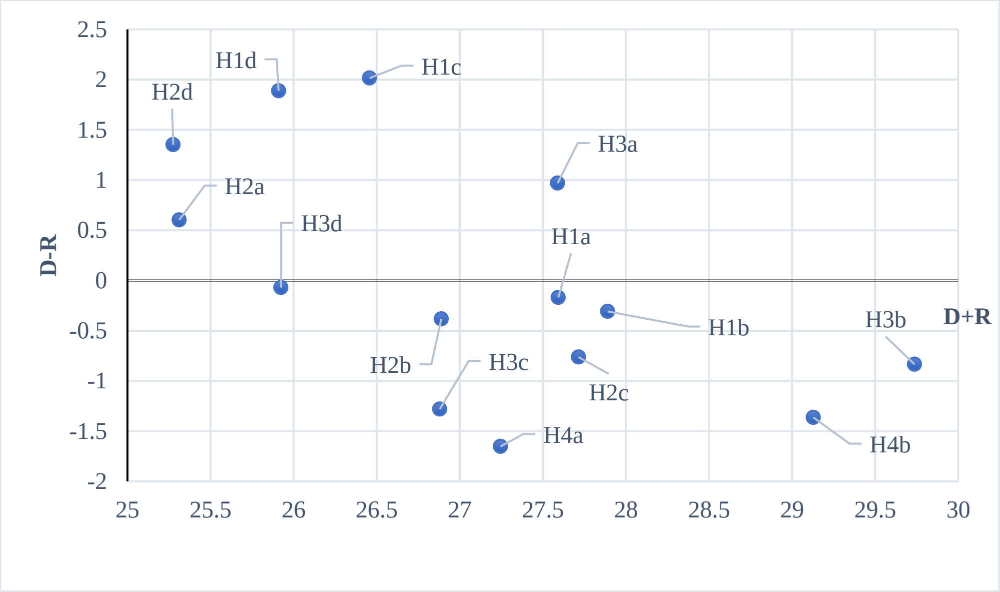

Figure 3. Causal relationships of driving influences.

We transformed the integrated impact matrix into an overall impact matrix, and based on expert advice and several trial calculations, we determined a threshold value of λ = 1.01. The process for calculating the reachable matrix is as follows.

$$k_{ij} = \begin{cases} 1, h_{ij} \geq \lambda \\ 0, h_{ij} \leq \lambda \end{cases} (\mathrm{i,j} = 1,2\ldots \mathrm{n}), \mathrm{K} = \left[k_{ij}\right]_{n\times n}$$

λ is the threshold value, and as the value of λ becomes larger, it becomes more obvious for structural simplification. In the actual analysis, the size of λ needs to be determined specifically according to the complexity of the system. k_{ij} is the value of the association between factor i and element j. The obtained reachable matrix is shown in Table 9.

The process for creating antecedent and reachable sets is as follows.

$$A(s_i) = \left\{s_j \in S \middle| k_{ij} = 1\right\}$$

$$R(s_i) = \left\{s_j \in S \middle| k_{ji} = 1\right\}$$

$A(s_i)$ is the set of antecedents, the set of elements corresponding to all rows in the S_ith column of the reachable matrix whose elements are 1.

$R(s_i)$ is the reachable set, the set of elements corresponding to all columns in the S_ith row of the reachable matrix whose elements are 1.

If $B(s_i) = \left\{ s_j \in S \,|\mathrm{R}(s_i) \cap \mathrm{A}(s_i) = \mathrm{A}(s_i) \right\}$, then $B(s_i)$ is the highest-level factor set. The antecedent set, the reachable set, and their intersection sets are shown in Table 10.

Table 9. Reachable matrix.

Factors	H1a	H1b	H1c	H1d	H2a	H2b	H2c	H2d	H3a	H3b	H3c	H3d	H4a	H4b
H1a	0	0	0	0	0	0	0	0	0	1	0	0	0	1
H1b	0	0	0	0	0	0	0	0	0	1	0	0	0	1
H1c	0	0	0	0	0	0	1	0	0	1	0	0	1	1
H1d	0	0	0	0	0	0	0	0	0	1	0	0	0	1
H2a	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H2b	0	0	0	0	0	0	0	0	0	0	0	0	0	1
H2c	0	0	0	0	0	0	0	0	0	1	0	0	0	1
H2d	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H3a	0	1	0	0	0	0	0	0	0	1	0	0	1	1
H3b	0	0	0	0	0	0	1	0	0	1	1	0	1	1
H3c	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H3d	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H4a	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H4b	0	0	0	0	0	0	0	0	0	1	0	0	0	0

Table 10. Predecessor sets, reachable sets, and their intersections.

Factors	Preliminary REVIEW $A(s_i)$	Accessible Collection $R(s_i)$	Intersections $B(s_i)$
H1a	1 7 10 11 13 14	1	1
H1b	2 7 10 11 13 14	2 9	2
H1c	3 7 10 11 13 14	3	3
H1d	4 7 10 11 13 14	4	4
H2a	5	5	5
H2b	6 7 10 11 13 14	6	6
H2c	7 10 11 13 14	1 2 3 4 6 7 9 10 14	7 10 14
H2d	8	8	8
H3a	2 7 9 10 11 13 14	9	9
H3b	7 10 11 13 14	1 2 3 4 6 7 9 10 14	7 10 14
H3c	11	1 2 3 4 6 7 9 10 11 14	11
H3d	12	12	12
H4a	13	1 2 3 4 6 7 9 10 13 14	13
H4b	7 10 11 13 14	1 2 3 4 6 7 9 10 14	7 10 14

We constructed a hierarchy of influencing factors that drive the adoption of smart construction technologies by companies according to the reachable matrix, as shown in

Table 11, and the ISM model diagram of influencing factors that drive the adoption of smart construction technologies by companies is shown in Figure 4.

Table 11. Hierarchy table.

Levels	Elemental Set	Level of Impact
L1	H2a, H2d, H3a, H3d	Surface impact
L2	H1a, H1b, H1c, H1d, H2b	Mid-level impact
L3	H2c, H3b, H4b	Deep impact
L4	H3c, H4a	Root images

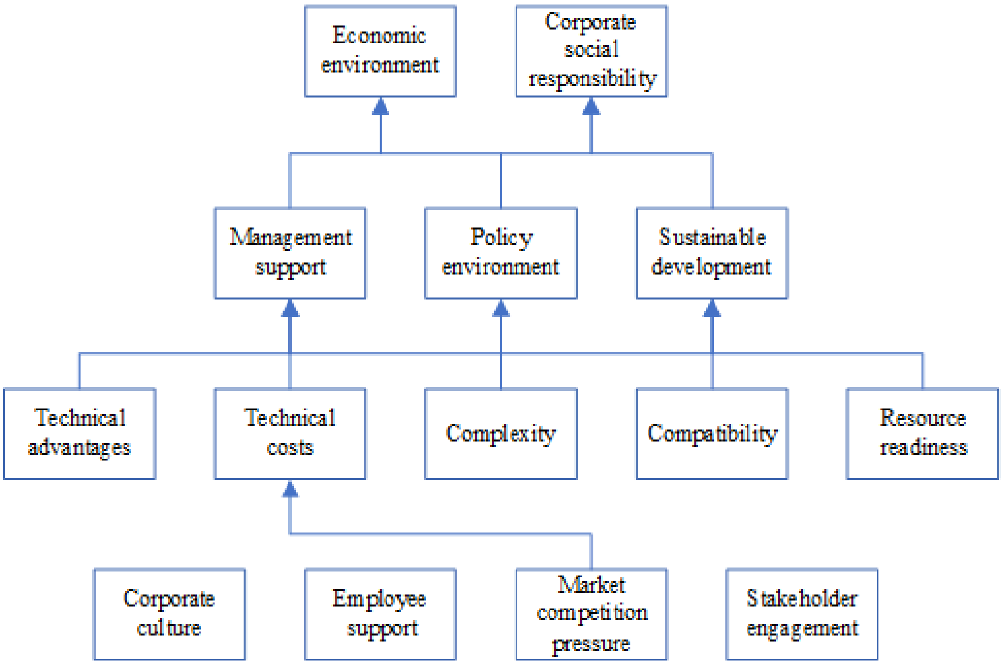

Figure 4. ISM hierarchy model of influencing factors driving company adoption of smart construction technologies.

5. Research Results

According to the Fuzzy DEMATEL–ISM calculations, the 14 hypotheses of the four dimensions of the Technology–Organization–Environment–Society framework proposed in this study, based on the TOE framework, all have varying degrees of driving influence, and the hypotheses are largely valid. The data in this paper were obtained using interviews and scoring of 25 experts and scholars, which was limited by the number of interviewees and their majors, and there may be differences if the results of this paper are applied to research on the adoption of intelligent construction in other fields. The specific findings of the study are as follows.

1. Policy environment (H3b), competitive market pressure (H3a), complexity (H1c), compatibility (H1d), and sustainability (H4b) have the highest degree of influence on other factors in the whole system of influencing factors, with the degrees of influence being 13.6629, 13.4321, 13.3896, 13.0722, and 13.0553, respectively. Policy environment (H3b), sustainable development (H4b), corporate social responsibility (H4a), senior management support (H2c), and economic environment (H3c) are the five most influenced factors, with the following levels of influence: 14.4496, 14.3389, 13.5905, 13.3943, and 13.3089, respectively. This indicates that these five factors are the most influenced by other factors.

2. Policy environment (H3b), sustainability (H4b), cost of technology (H1b), senior management support (H2c), and technological advantage (H1a) are the most significant in the system of influencing factors that drive the adoption of smart construction technologies by companies, with D+C values of 28.1124, 27.3942, 26.2329, 26.0686, and 25.9555, respectively. Employee support (H2d), corporate culture (H2a), compatibility (H1d), stakeholder involvement (H3d), and complexity (H1c) are the five factors with the lowest D+C values of 23.7724, 23.8075, 24.3702, 24.3838, and 24.8846, respectively, indicating a relatively weak influence on the system.
3. Positive D-C values for complexity (H1c), compatibility (H1d), employee support (H2d), competitive market pressure (H3a), and corporate culture (H2a) indicate that these factors are causal factors, that they have an active influence on companies' adoption of smart construction technologies, and that they are less influenced by other factors. Stakeholder involvement (H3d), technological advantage (H1a), technology cost (H1b), resource readiness (H2b), senior management support (H2c), policy environment (H3b), economic environment (H3c), sustainability (H4b), and corporate social responsibility (H4a) have negative D-C values, meaning that they are outcome factors that are influenced by other factors and thus drive the adoption of smart building technologies.
4. We used a hierarchy based on the Interpretive Structural Model (ISM) to classify the influencing factors affecting the adoption of smart construction technologies by companies into four levels. The first level of influence is the surface level, which includes four factors: corporate culture (H2a), resource readiness (H2b), competitive market pressure (H3a), and stakeholder involvement (H3d). The second level of influence is the middle level, which consists of five factors: technological advantage (H1a), technological cost (H1b), complexity (H1c), compatibility (H1d), and resource readiness (H2b). The third level is the deeper level of influence, which consists of three factors: top management support (H2c), economic environment (H3c), and sustainability (H4b). The fourth level is the root cause, which includes two factors: economic environment (H3c) and corporate social responsibility (H4a).
5. Of the four influencing factors in the technological dimension, namely, technology advantage (H1a), technology cost (H1b), complexity (H1c), and compatibility (H1d), two factors have positive D-C and are causal factors. Two factors have a greater degree of influence, which indicates that the influencing factors of the technological dimension have the most significant degree of influence on driving the adoption of smart construction technologies by highway construction companies. This is in line with the findings of Yang et al., Porwal and Hewage, and Rezgui et al., who concluded that, when deciding to adopt a complex innovation such as SBT, governments need to prioritize technologies/instruments capable of capturing all information [32,33,36]. This study shows that "complexity" and "compatibility" are the main factors of "technical dimension influencing factors", while "technical dimension influencing factors" are the decisive factors influencing the adoption of intelligent construction technology by expressway companies, which is the highest priority of the interviewed experts and scholars.
6. The organizational dimensions of top management support (H2c) and employee support (H2d) have a high degree of influence on the system of factors driving highway construction companies to adopt smart construction technology, which means that the process of companies adopting smart construction technology should focus on training company personnel, especially when adopting innovative technologies; on the degree of the personnel's understanding of the technology; and on precise cooperation during operations, which can make the adoption of smart construction technologies easier. This is the same as the conclusion as those of Eadie et al. and Cao et al.: what influences the adoption of BIM technology in China is the support of senior managers and customers [27,28]. In addition, according to the research in this paper, resource readiness directly affects the cost of technology, but the authors believe

that cost should not be the main obstacle to the adoption of intelligent construction technology by highway construction companies, because the long-term economic benefits after adoption can compensate.

7. In the environmental dimension, competitive market pressure (H3a) and policy environment (H3b) have a significant impact on the adoption of smart construction technologies and other factors in the system. This suggests that the environmental dimension is a key consideration in the adoption of smart construction technologies, which is the same conclusion as Miettinen et al. [34]. In the results of this paper, stakeholders are less important, which contradicts the findings of previous scholars such as Singh et al. [45]. In our opinion, the possible reason is that the interviewees were all experts in the field of highway construction or university scholars in the field of engineering management, and did not include enterprise experts and personnel in the investment, consulting, and design of expressway construction. However, this does not affect the validity of the results of this study, because the research object of this paper is only highway construction enterprises, and if the field of replacement is studied, the results of this paper can be used for reference but need to be investigated further.
8. We innovatively present the influencing factors of the social dimension, including corporate social responsibility (H4a) and sustainability (H4b). According to the results of the analysis, the degree to which sustainability (H4b) influences other factors in the system and drives the adoption of smart construction technologies is highly significant. Corporate social responsibility (H4a), however, belongs to the root influence level of the ISM hierarchy model. This shows that the combination of corporate social responsibility and sustainability strongly drives highway construction companies to adopt smart construction technology, which is basically the same as Avotra et al.'s research [64]. At the same time, this also shows that the social influences proposed in this paper are important in the system of influences that drive highway construction companies to adopt smart construction technologies, and they provide empirical evidence and new research ideas for subsequent scholars.

6. Empirical Analysis

In order to verify the effectiveness of this paper in practical applications, the author contacted three heads of a subsidiary of China Communications Construction Co., Ltd., which belongs to the world's top 500 enterprises, under the condition of explaining the research results of this paper one by one, and combined with practical engineering applications. The three responsible persons re-scored the scoring questionnaire. Through the same calculation as Chapter 4 of this paper, the author communicated with the respondents separately, and finally obtained the following empirical analysis results:

1. The calculation results of the empirical analysis are basically the same as those calculated in this paper, in which the technical advantage (H1a) changes to the third level of deep impact, and stakeholder participation (H3d) and market competitive pressure (H3a) jointly affect the cost of technology (H1b), as shown in Figure 5.
2. Among the four dimensions proposed in this paper, the influencing factors of the technical dimension are the priority of the respondents and are the key to influencing whether the main leaders of highway construction enterprises adopt intelligent construction technology. Among them, technology advantage (H1a) and technology cost (H1b) are the factors with high influence.
3. Considering the influencing factors of the social dimension with the actual situation, in the process of discussion with the respondents, it was understood that, as one of the important engineering enterprises in our country, the company must have a sense of corporate social responsibility (H4a) and shoulder the important task of developing intelligent building technology, improving engineering production efficiency, and improving the ability for technical innovation.

4. On the whole, the results of the empirical analysis are basically the same as the research results in this paper, which fully proves that the validity and generalizability of the research results of this paper are significant and provides reference and experience for the research field of intelligent construction technology adopted by highway construction enterprises.

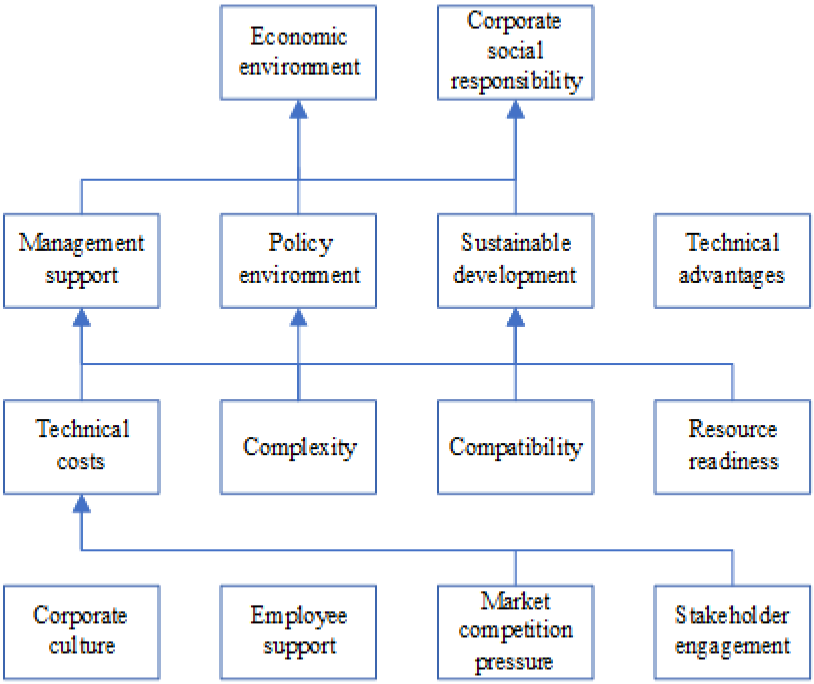

Figure 5. Empirical analysis of the ISM hierarchy model.

7. Discussions and Conclusions

Based on the national and international literature, we first summarized the multifaceted nature of the motorway construction field. Then, to benefit from theories developed in different knowledge systems, we invited 25 experts, scholars, and professionals in the field to participate in the study through expert interviews, summarizing and refining the driving influences in four dimensions: technical, organizational, environmental, and social. We established the TOSE framework based on the TOE framework, which, to some extent, increases and expands the adoption of smart construction research in this field. This adds to and extends the experience of applying the TOE framework to research in the field of smart construction. The number of experts that were involved was 25, which may be a limitation of this study. However, the focus of this study was on experienced experts in the field rather than on the number of experts. Finally, by applying the Fuzzy DEMATEL–ISM method to analyze the results of the expert scoring, we found that the hypotheses regarding the 14 influencing factors hold true and that each factor has a driving influence on the adoption of smart construction technology by highway construction companies in China to varying degrees. Among them, the degree of influence of the influencing factors of the technological dimension is the strongest, coinciding with previous research findings, which also laterally demonstrates the authenticity and reliability of the results of this study.

Because of the above findings, the results of this study can help decision makers and managers of highway construction companies to understand the various influencing factors of the adoption of smart construction technology in their companies in future practice, which is an important reference value for the decision making of highway construction companies in the application of smart construction technology. In addition, this study has implications for the adoption of smart construction technology in other areas of the construction industry. Although this study focuses on highway construction companies, which are different from other companies in the construction industry, the influencing factors presented in this paper can be added to and subtracted from future discussions to fill in the gap in research on the influencing factors of other companies in the adoption of smart construction technology. To further develop and promote the application of smart construction technology in the construction industry, to achieve sustainable development for the smart construction of buildings, and to improve the smart construction of buildings, we recommend that companies learn about and conduct training for smart construction technology.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15010703/s1, File S1: Blank Expert Scoring Questionnaire.

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Informed Consent Statement: The expert interviews and expert scores involved in this study have obtained the informed consent of the interviewees.

Data Availability Statement: The study data for this study are publicly available and can be obtained by contacting the corresponding authors.

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