

Article

Effect of Smart Construction Technology Characteristics on the Safety Performance of Construction Projects: An Empirical Analysis Based on Structural Equation Modeling

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Abstract: The application of smart construction technologies is becoming a crucial approach to improving safety performance in the construction industry. Existing research often focuses on the qualitative analysis of specific technologies, neglecting a comprehensive empirical examination of the characteristics of smart construction technologies and their impact on project safety performance. This study identifies five principal characteristics of smart construction technology: integration, automation, initiative, shareability, and sustainability. By integrating the technology acceptance model (TAM) and the task–technology fit (TTF) model, we propose a theoretical path of “technology characteristics–perceived behavior–behavioral intention–safety performance” and develop a structural equation model to assess the effect of these characteristics on safety performance. The results indicate that these characteristics have a significant direct impact on safety performance, with the estimated direct effect reaching as high as 0.61. Additionally, these characteristics positively influence safety performance indirectly through mediating variables such as perceived ease of use, perceived usefulness, usage intention, and usage behavior. This study empirically verifies the pathways through which smart construction technology characteristics affect safety performance, providing theoretical support for the widespread application of these technologies in construction engineering and enhancing safety management.

Keywords: smart construction; technical characteristics; safety performance; technology acceptance model; structural equation modeling



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1. Introduction

In construction, safety issues have always been the focus of attention. The unique nature of the construction industry, such as the uniqueness of construction projects and high mobility of labor, the difficult and harsh working conditions, chaotic management of subcontractors, and weak safety management of small- and medium-sized construction enterprises, have led to the high rate of safety accidents in the construction industry [1,2]. In recent years, smart construction has garnered significant attention in the construction industry as a novel construction mode. This mode leverages advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), and sensors to achieve digital and intelligent management throughout the construction lifecycle [3–5]. With the deepening of informatization and the advent of intelligent construction, smart construction technology is gradually being implemented in specific engineering projects. The application of smart construction technology is becoming an important means to improve the safety performance of construction projects [6].

Existing research underscores a close relationship between the application of smart construction technology and safety management [7]. For instance, IoT-based sensing and

wearable devices can provide real-time monitoring and alerts, enhancing workers' safety [8]. Similarly, building information modeling (BIM) improves safety management through better visualization and hazard identification [9]. By introducing advanced technologies, the real-time monitoring of engineering progress, the identification of potential safety hazards, and the provision of early warnings become feasible [10]. Additionally, the use of intelligent and automated equipment can mitigate the risks associated with hazardous working environments, thereby reducing the likelihood of accidents [11,12]. These technologies also enhance construction efficiency and optimize resource allocation, offering robust support for safety management.

Several studies have empirically examined the impact of smart construction technologies on safety performance. For example, Li et al. [13] used IoT-based sensing and wearable devices for proactive behavior-based safety management, demonstrating substantial improvements in construction safety. Similarly, Zhang et al. [14] utilized BIM to enhance safety through the automatic safety checking of construction models and schedules. Azhar et al. [15] provided empirical evidence on the effective use of BIM in improving project safety. These studies generally support the positive impact of smart construction technologies on safety performance, but they often focus on specific technologies rather than providing a comprehensive view.

Although existing research has discussed the effectiveness of smart construction technology in engineering safety management, research content still has room for further exploration. First, previous evaluations and impact studies of smart construction technology often focused on specific information technology applications or information management practices [16], which do not accurately reflect the overall characteristics of smart construction technology and make it difficult to construct a complete theoretical pathway to explain how smart construction technology affects engineering projects. Moreover, existing studies often qualitatively describe the relationship between specific smart construction technologies and safety performance, lacking quantitative evaluations and specific empirical analysis. Research on how smart construction technology affects safety performance from an empirical perspective is relatively few, and this research gap may limit the understanding of the true potential of smart construction technology in enhancing project safety.

In this context, the relationship between the characteristics of smart construction technology and safety performance has not been sufficiently explored. This limitation not only makes it difficult for the government to formulate policies to promote the development of smart construction but also poses challenges for construction companies in making decisions concerning technology selection and use. Therefore, this study first identifies relevant evaluation indicators for smart construction technology characteristics and safety performance through the literature review. Then, it integrates the technology acceptance model (TAM) and the task–technology fit (TTF) model to construct a complete theoretical impact pathway of smart construction technology characteristics on safety performance. Data are collected through surveys and interviews to build structural equation modeling, which is used to test the proposed theoretical impact pathway empirically. By thoroughly researching the characteristics of smart construction technology and their impact on safety performance, this study aims to provide reference significance for the application of smart construction technology in construction projects and the improvement of safety performance.

2. Literature Review

2.1. Characteristics of Smart Construction Technology

The characteristics of smart construction technology refer to the fundamental elements and features exhibited during the implementation of engineering construction and management processes. Although current research on the characteristics of smart construction technology is still somewhat limited, international scholars have made a series of remarkable achievements in related fields. Eastman et al. [17] discussed in detail how building information modeling (BIM) improves supervision and coordination in construction

projects. These technologies support various construction activities, such as supervision, coordination, training, and information processing, by providing detailed information and a high degree of visualization. Love et al. [18] discussed the implementation of BIM and its role in promoting integration throughout the various stages of construction projects (from design to operation). In the field of smart buildings, especially in prefabricated construction, the integrated application of systems and production processes is crucial. BIM supports data sharing and collaborative work, which is essential for the efficient delivery of prefabricated components.

The availability of timeliness and real-time information is crucial for the success of smart building systems. Wang et al. [19] studied how real-time data acquisition and communication technology can improve construction project management, enhance decision-making processes, and increase operational efficiency. Boje et al. [20] described the application of digital twin technology in achieving real-time, remote, and interactive aspects of projects. These technologies enable project teams to monitor construction progress in real time and effectively manage remotely, thereby improving overall efficiency and responsiveness. Finally, regarding the comprehensive application of smart construction technology and the integration of production processes, Succar and Kassem [4] explored the macrolevel application of BIM technology, including the integration of design, production, and construction. Their research indicates that through the integration of application systems, single-point application systems can not only share data with multiple systems but also support collaborative work among multiple participants.

In summary, the technical characteristics of smart construction have received extensive attention from international scholars. This study collated and organized the smart construction technology characteristics mentioned in the existing literature, as shown in Table 1.

Table 1. Characteristics of smart construction technologies.

Characteristics	Statement Interception	Related Research
Flexibility	Adapt to changes in user needs	[21,22]
Reliability	Trusted to accomplish required operations through smart construction technology	[23,24]
Integration	Information sharing between project participants or the fusion of information from different systems	[25,26]
Immediacy	The currency of the information provided by information technology	[21,27]
Presentation	The extent to which smart construction technology information is appropriately presented	[23,28]
Automation	Use computers or electronic information tools to process data or produce products	[5,29]
Initiative	Provide timely and up-to-date information and predict future conditions	[30,31]
Shareability	Exchange and sharing of information data between different levels and departments	[3,32]
Accuracy	Users perceive that the information provided by smart construction technology is appropriate and accurate	[33,34]
Sustainability	Smart construction technology covers the entire life cycle of the building during use and forms a sustainable experience	[20,35]

2.2. TAM and TTF Model

The impact of smart construction technologies on safety performance is manifested in the adoption behavior of users. Although smart construction technology has significant appeal, users must widely accept and use it to unleash its true potential [16]. Advanced applications of information technology enhance individual efficiency and reliability, making the recording and organizing of information more powerful [36,37]. They enrich,

complicate, and mobilize the acquisition of information and knowledge [38], ultimately enhancing performance.

The TAM, proposed by Davis et al. [39] on the basis of the theory of reasoned action and the theory of planned behavior, explores the key factors influencing the adoption of information technology. This model suggests that the perceived usefulness and perceived ease of use of a technology are the primary determinants of its acceptance. Perceived usefulness refers to the degree to which an adopter believes that using a technology will improve their job performance, while perceived ease of use refers to the ease with which an adopter believes they can use the technology. In this model, external characteristics influence perceived usefulness and perceived ease of use, and perceived ease of use may have an impact on perceived usefulness. These factors jointly affect the willingness to adopt technology, further influencing actual adoption behavior. On the basis of the TAM model, numerous scholars have conducted empirical research on the impact of adoption behavior generated by information technology perception. Researchers often focus on the factors influencing technology adoption [40], with less attention to the further impact of technology adoption on individual or corporate performance [41].

In 1995, Goodhue and Thompson [42] introduced the TTF theory, which established the “technology to performance chain” framework to explore the impact of technology characteristics on user performance. Goodhue [43] defined the most representative variable in this theory, i.e., TTF, as “users’ perception of the extent to which an information system or service meets their task needs”. Task characteristics, technology characteristics, and individual characteristics also affect the TTF variable.

Dishaw and Strong [44] successfully integrated the TAM and the TTF model and confirmed the explanatory power of the new model. They found that technology characteristics positively affect perceived ease of use, perceived usefulness, and TTF. In their study of e-commerce applications, Kloppe and McKinney [45] further explored the impact of technology characteristics on perceived ease of use and TTF. Their empirical results validated all hypothesized relationships and demonstrated that the new model more effectively predicts consumer behavioral intentions. Some scholars consider the core variable of TTF and the core variables of perceived ease of use and perceived usefulness in TAM as parallel factors, exploring their impact on outcome variables. For example, on the basis of TTF theory and TAM, Klaus et al. [46] proposed a conceptual model for explaining usage performance with a survey of 222 students, finding that improving users’ perceived TTF, perceived usefulness, and perceived ease of use can enhance their performance on the internet. Yen et al. [47] focused on the adoption willingness of enterprise employees toward wireless technology, finding through surveys in manufacturing, service, and financial industries that TTF, perceived ease of use, and perceived usefulness are important antecedents of wireless technology adoption willingness. Additionally, a few studies have expanded TTF theory at the individual [48], group [49], and organizational levels [50], aiming to explore the impact of information technology adoption and use on performance.

The characteristics of smart construction technologies significantly impact the safety performance of construction engineering projects [51], but this impact depends not only on the technology itself but also closely on the adoption behavior of managers and construction personnel. Considering the application of smart construction technologies in construction project management and construction tasks, our study views the user adoption of smart construction technologies as an organizational innovation behavior. Starting from the perceived usefulness and perceived ease of use of smart construction technologies, this study examines the willingness to use these technologies, thereby explaining the adoption behavior of smart construction technologies. The variables of perceived usefulness, perceived ease of use, and usage willingness are selected as the basic indicators affecting the adoption behavior of smart construction technologies, and these factors ultimately impact the safety performance of construction projects.

In the field of construction engineering, although many practical studies have been conducted on the correlation between specific smart construction technologies and safety

performance, research on how smart construction technologies affect safety performance is relatively lacking. This gap in empirical research may limit the understanding of the true potential of smart construction technologies in enhancing project safety. Moreover, existing research often focuses on the impact of individual technology characteristics on specific aspects of project safety management, lacking a comprehensive study on the systematic identification of smart construction technology characteristics and their impact on safety performance. Additionally, in most engineering practices, smart construction technologies are used as either single or multiple independent technologies rather than as integrated solutions, leading to communication difficulties among project participants and hindering the management of the entire lifecycle of construction projects. In this context, the relationship between the characteristics of smart construction technologies and project safety performance has not been adequately explored. Therefore, this study integrates the TAM and TTF model to identify the characteristics of smart construction technologies systematically and investigate the impact of these characteristics on project safety performance deeply, thereby providing improved guidance for policy-making and practical application.

3. Methodology and Data

3.1. Model Specification

Structural equation modeling (SEM) is a multivariate statistical analysis technique used to analyze and estimate complex causal relationship models. It is widely applied in fields such as social sciences, behavioral sciences, market research, and educational research. SEM analyzes causal relationships between latent variables by using structural equation models composed of directly measurable observed variables and represents these causal relationships through causal models, path diagrams, and other means. In this study, AMOS 24.0 software is used for model analysis.

This study integrates the TAM and the TTF model from the perspective of technology perception and adoption behavior to analyze the impact of smart construction technology characteristics on the safety performance of construction engineering projects. The variables in two dimensions—technology perception (perceived usefulness or perceived ease of use) and technology adoption behavior (intention and usage)—are considered important factors influencing safety performance due to smart construction technology characteristics. A conceptual relational path model is established, as shown in Figure 1. This model involves six variables, where smart construction technology characteristics are the independent variables, safety performance is the dependent variable, and perceived usefulness, perceived ease of use, intention to use, and usage behavior are the mediating variables. On this basis, nine hypotheses are proposed, as detailed in Table 2.

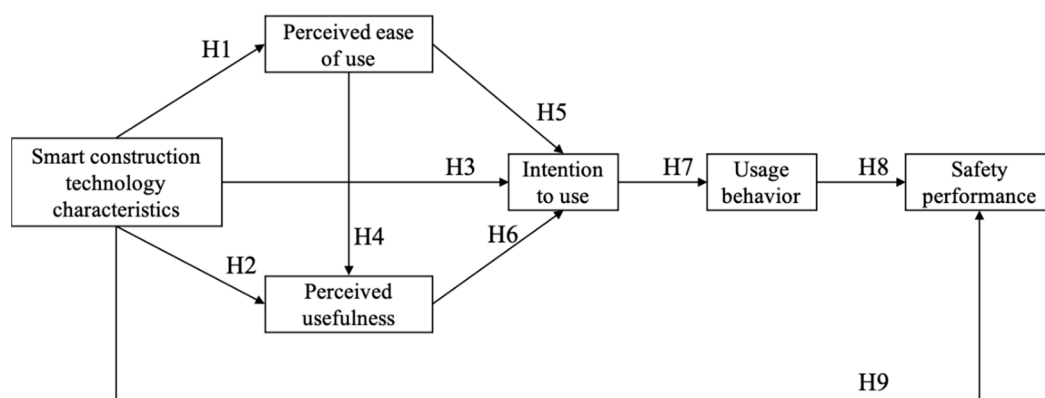


Figure 1. Conceptual model.

Table 2. Research hypotheses.

Hypotheses	
H1	Smart construction technology characteristics have a positive impact on perceived ease of use.
H2	Smart construction technology characteristics have a positive impact on perceived usefulness.
H3	Smart construction technology characteristics have a positive impact on intention to use.
H4	Perceived ease of use has a positive impact on perceived usefulness.
H5	Perceived ease of use has a positive impact on intention to use.
H6	Perceived usefulness has a positive impact on intention to use.
H7	Intention to use has a positive impact on usage behavior.
H8	Usage behavior has a positive impact on safety performance.
H9	Smart construction technology characteristics have a positive impact on safety performance.

3.2. Core Variable Measurement

3.2.1. Smart Construction Technology Characteristics

Through semistructured interviews and scattered guided interviews with informed experts involved in large construction projects, the characteristics of smart construction technologies were inductively screened. This study invited a team of 10 experts, including technical business leaders from engineering authorities, representatives of project design units, heads of construction project companies, and representatives of safety management technicians. The invited experts were asked to score the 10 smart construction technology characteristics summarized in Table 1, considering these characteristics as the fundamental elements and characteristics demonstrated and represented by smart construction technologies. The scoring range was from 1 (strongly disagree) to 7 (strongly agree), and the results are shown in Table 3.

Based on a comprehensive review of the existing literature, project surveys, expert scoring, and expert interview results, this study selects five indicators to characterize the characteristics of smart construction technologies: integration, automation, initiative, shareability, and sustainability.

Table 3. Expert scoring statistics.

Characteristics	Expert Average Score	Variation
Flexibility	3.4	0.14
Reliability	3.2	0.25
Integration	4.5	0.11
Immediacy	3.7	0.27
Presentation	3.3	0.18
Automation	4.6	0.11
Initiative	4.5	0.11
Shareability	4.4	0.14
Accuracy	3.3	0.21
Sustainability	4.5	0.11

3.2.2. Engineering Safety Performance

The concept and measurement of safety performance in academia generally include objective indicators at the organizational level of enterprises and safety behavior performance at the individual level of employees. This study evaluates safety performance at individual and project levels. This evaluation not only identifies trends and patterns in safety management [52] but also helps determine the root causes of accidents and incidents at construction sites [53], thus offering an in-depth understanding and potential improvements in safety performance.

Individual safety performance refers to an individual's contribution and performance regarding safety during work, typically encompassing the comprehensive performance of safe behavior at work [54]. It reflects an individual's awareness and attitude toward safety and directly impacts workplace safety conditions. The assessment of individual safety performance typically includes three aspects: safety awareness, safety behavior, and safety outcomes [55]. Safety awareness refers to a person's degree of cognition and understanding of safety, including mastery of safety knowledge, the ability to judge hazardous behavior, and compliance with safety regulations and policies. Enhancing safety awareness can effectively reduce the occurrence of accidents. Safety behavior refers to the safety-related actions a person takes at work, such as exercising safety duties. Performance can be quantitatively assessed through safety behavior evaluations to determine the current state and direction of improvement in safety work [56]. Safety behavior evaluation includes four aspects: behavioral norm evaluation, risk identification evaluation, emergency response evaluation, and personal quality evaluation. Safety outcomes refer to the safety-related results produced during work, such as accidents and near-miss incidents. The occurrence of these outcomes can reflect whether safety hazards are present in a person's work and their level of attention to safety.

The safety performance of engineering projects is an assessment of the effectiveness of safety control measures across management, technical, and regulatory dimensions, used to measure the actual safety achievements of all collaborating units [57,58]. In terms of project safety performance evaluation, this study focuses on corporate safety culture, safety metrics, safety management capabilities, and safety investments [59]. Corporate safety culture refers to the common values and behavioral norms that reflect the attention employees and the company pay to safety. This culture includes aspects such as safety awareness, safety training, safety management systems, and safety standards and is an important component of corporate safety management. Safety metrics are a way to reveal the safety status of a company in data form, such as the frequency of safety accidents, the number of safety hazards, the compliance rate of safety inspections, and safety review scores. These metrics help companies timely discover and identify safety risks and manage and control them accordingly. Safety management capability refers to the safety management abilities a company needs to possess, including risk assessment, early warning, emergency response, and safety training capabilities [60]. These capabilities help the company identify and respond to various safety risks, reduce the incidence of safety accidents, and improve the level of safety assurance. Safety investments refer to the financial and human resources that a company needs to allocate for safety management, such as purchasing safety equipment, training employees, and establishing safety standards, to enhance the company's level of safety assurance [61]. By investing adequately in safety management, companies can prevent and control safety risks well, thereby providing reliable protection for the safety of employees and the company.

3.3. Questionnaire Design and Data Analysis

3.3.1. Questionnaire Design

A survey questionnaire was designed to collect relevant research data to investigate the impact of smart construction technology characteristics on engineering safety performance. The questionnaire included four sections, with the first part collecting the personal information of the respondents, such as gender, age, educational background, and occupation. The remaining parts covered six main latent variables: characteristics of smart construction technologies, perceived ease of use, perceived usefulness, intention to use, usage behavior, and safety performance. The measurement scales for these latent variables are detailed in Table A1 of Appendix A. All scales were measured using a seven-point Likert scale.

This study employed online and offline surveys, targeting professionals in the field of construction engineering across seven provinces in China, including Shanghai, Zhejiang, Jiangsu, Anhui, Jiangxi, Hunan, and Hubei. A total of 856 questionnaires were collected.

After invalid questionnaires were excluded, a total of 742 questionnaires were finally used for empirical analysis in this research.

3.3.2. Descriptive Statistics

A descriptive statistical analysis of the valid questionnaires shows that the majority of the respondents are male, accounting for 83.8% of the sample. The educational background of the respondents is primarily bachelor's and associate degrees or below, accounting for 54.2% and 34.9%, respectively. The age of respondents is mainly concentrated between 25 and 35 years old (38.8%) and between 35 and 45 years old (34.4%), followed by those over 45 years old (22.9%), indicating that the sample primarily consists of middle-aged and young adults. The types of organizations respondents work for are mainly general contractors (78.0%), with owners, design firms, subcontractors, government units, and operations and maintenance sides accounting for 16.7%, 0.8%, 3.0%, 0.8%, and 0.5%, respectively. The distribution of years of experience in the construction industry among the respondents is average, with 5–10 years (31.9%), 10–15 years (24.3%), and over 16 years (25.9%). Among the respondents, 57.8% have three or more years of experience related to smart construction, accounting for over half of the total number of respondents. The sample data meet the requirements for sample characteristics for this study.

3.3.3. Reliability and Validity Analysis

This study utilized SPSS 26.0 for reliability and validity analyses to test the reliability and validity of the questionnaire data. The Cronbach's alpha coefficient was used to assess the reliability of the scales, and the results are displayed in Table 4. The Cronbach's alpha values for each latent variable were all above 0.9, with an overall reliability of 0.919, indicating a high level of reliability and suggesting that the questionnaire data are highly reliable.

Table 4. Reliability and validity test.

	Latent Variable	Number of Items	Cronbach's α	KMO	CR	AVE
IN	Integration	4	0.926	0.854	0.938	0.791
AU	Automation	4	0.954	0.838	0.959	0.854
INI	Initiative	4	0.934	0.854	0.942	0.802
SH	Shareability	4	0.929	0.839	0.945	0.810
SU	Sustainability	4	0.938	0.806	0.935	0.784
PU	Perceived usefulness	5	0.900	0.886	0.913	0.677
PE	Perceived ease of use	5	0.929	0.886	0.939	0.755
ITU	Intention to use	7	0.937	0.942	0.944	0.707
UB	Usage behavior	6	0.945	0.928	0.918	0.653
ISP	Individual safety performance	10	0.932	0.960	0.938	0.602
PSP	Project safety performance	10	0.931	0.959	0.938	0.601
Overall			0.919	0.916		

According to Table 4, the KMO values for all the latent variables are above 0.8, with an overall KMO value of 0.916. The *p*-values for Bartlett's test of sphericity are less than 0.05, indicating that the scales have acceptable validity. Factor analysis was conducted on the questionnaire data, using the maximum variance method to extract factors based on eigenvalues greater than one, resulting in a total variance explained of 74.94%. The results of the factor analysis, shown in Appendix A, indicate that the postrotation factor loadings range from 0.703 to 0.962, all exceeding 0.7, thus demonstrating a good correlation between the latent variables and their observed variables. The composite reliability (CR) for each latent variable is greater than 0.7, and the average variance extracted (AVE) for each is greater than 0.5, suggesting good convergent validity. As shown in Table 5, the square root of each latent variable's AVE is

greater than the correlation coefficients between that latent variable and other latent variables, indicating good discriminant validity. Overall, the measurement scales and the collected data samples in this study exhibit good reliability and validity.

Table 5. Discriminant validity analysis.

Latent Variable	IN	AU	INI	SH	SU	PU	PE	ITU	UB	ISP	PSP
IN	0.791										
AU	0.088	0.854									
INI	0.163	0.184	0.802								
SH	0.103	0.075	0.068	0.810							
SU	0.186	0.194	0.164	0.180	0.784						
PU	0.230	0.195	0.242	0.142	0.215	0.677					
PE	0.099	0.172	0.158	0.120	0.202	0.122	0.755				
ITU	0.044	0.011	0.070	0.087	0.105	0.244	0.218	0.707			
UB	−0.033	−0.026	0.018	−0.009	0.029	0.097	0.035	0.258	0.653		
ISP	0.136	0.168	0.128	0.173	0.163	0.129	0.132	0.088	0.418	0.602	
PSP	0.085	0.134	0.126	0.117	0.134	0.131	0.097	0.135	0.445	0.219	0.601
Square root of AVE	0.889	0.924	0.896	0.090	0.885	0.823	0.869	0.841	0.808	0.776	0.775

4. Model Analysis and Results

4.1. Fitness Test and Path Analysis

4.1.1. Model Fitness Test

A structural equation model was constructed using AMOS 24.0 software, and the structural equation model was analyzed using the maximum likelihood method. The results from the model fitness test showed that the chi-square to degrees of freedom ratio (CMIN/DF) is 1.048, which is within the excellent fit range of 1–3. The RMSEA is 0.008, which is less than 0.05 and meets the recommended value. Additionally, the CFI, TLI, and IFI are all greater than 0.9, meeting the recommended standards. In summary, the model established in this study is considered to have good fitness and is suitable for further path analysis.

4.1.2. Model Path Analysis

The path significance coefficients between the latent variables are shown in Table 6. In the original model, among the nine paths between the latent variables, seven were significant and two were not. Specifically, the impact of smart construction technology characteristics on intention to use was not significant, which does not support hypothesis H3. This result suggests that the influence of smart construction technology characteristics on intention to use must be explained through other mediating variables. Additionally, the path between perceived ease of use and perceived usefulness was not significant, which does not support hypothesis H4. After the unsupported hypotheses were removed, the final research model was obtained.

Table 6. Model path testing results.

	Path	Estimate	S.E.	C.R.	<i>p</i>	
H1	Perceived ease of use ←— Characteristics	0.382	0.155	5.546	***	Y
H2	Perceived usefulness ←— Characteristics	0.493	0.147	6.388	***	Y
H3	Intention to use ←— Characteristics	−0.084	-	-	-	N
H4	Perceived usefulness ←— Perceived ease of use	−0.04	-	-	-	N
H5	Intention to use ←— Perceived ease of use	0.206	0.041	4.773	***	Y
H6	Intention to use ←— Perceived usefulness	0.264	0.055	5.312	***	Y
H7	Usage behavior ←— Intention to use	0.264	0.043	7.027	***	Y
H8	Safety performance ←— Characteristics	0.606	0.092	5.947	***	Y
H9	Safety performance ←— Usage behavior	0.910	0.026	12.894	***	Y

Note: *** $p < 0.01$.

4.2. Analysis of Model Estimation Results

The revised structural equation model was run using AMOS 24.0. Figure 2 displays the standardized estimation coefficients of the structural equation model. Smart construction technology characteristics have a significant impact on perceived ease of use and perceived usefulness, supporting hypotheses H1 and H2. The path coefficients are 0.37 and 0.48, respectively, indicating that smart construction technology characteristics significantly enhance users' perceptions of its usefulness and ease of use.

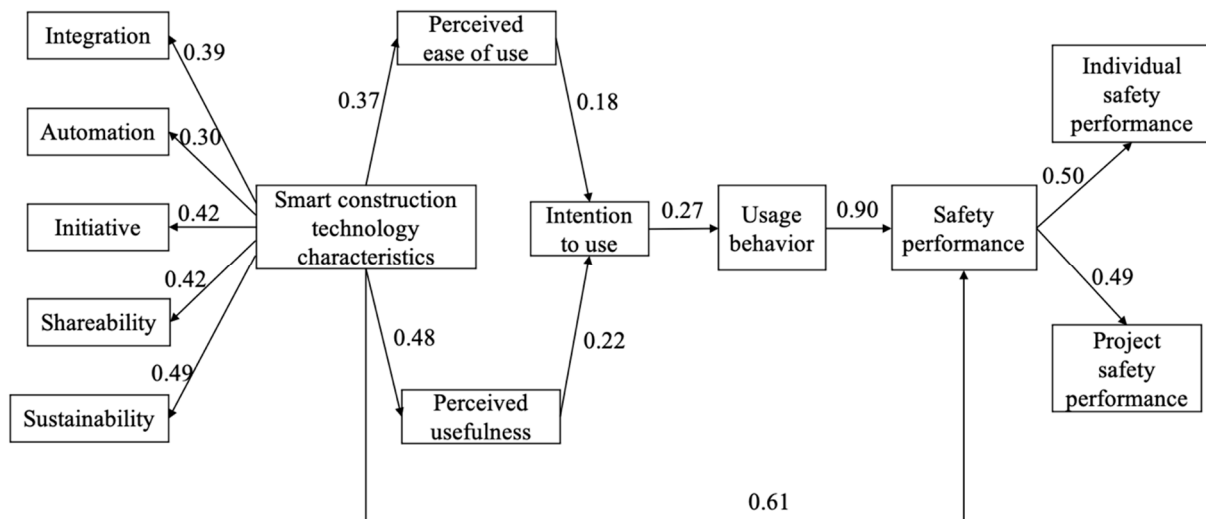


Figure 2. Standardized regression coefficients of the structural equation model.

Perceived ease of use and perceived usefulness have a significant positive impact on usage intention, supporting hypotheses H5 and H6. The path coefficients are 0.18 and 0.22, respectively, demonstrating that the higher the users' perceptions of the ease of use and usefulness of smart construction technology characteristics, the greater their willingness to use them.

Intention to use has a significant positive impact on usage behavior, supporting hypothesis H7. The path coefficient is 0.27, indicating that the stronger the users' intention to use smart construction technology, the more likely they are to engage in actual usage behavior.

Usage behavior has a significant positive impact on safety performance, supporting hypothesis H8. The path coefficient is 0.90, indicating that the more frequently users engage in the usage behavior of smart construction technology, the better their performance in terms of safety.

At a significance level of 0.01, the path coefficient from "smart construction technology characteristics to safety performance" is 0.61, further supporting hypothesis H9. This finding suggests that smart construction technology characteristics have a significant positive impact on engineering safety performance. The magnitude of the coefficient indicates a significant relationship between the enhancement of smart construction technology characteristics and the improvement of engineering safety performance.

4.3. Analysis of the Impact on Safety Performance

This section further explores the effects and mechanisms of smart construction technology characteristics on engineering safety performance by analyzing direct and indirect effects. The direct effect value is the standardized path coefficient between two variables in the path diagram; the indirect effect value is the product of the path coefficients.

Smart construction technology characteristics have a direct impact on safety performance, with the "smart construction technology characteristics–safety performance" path having a standardized regression coefficient of 0.61. In the path "smart construction technology characteristics–perceived ease of use–intention to use–usage behavior–safety

performance”, the indirect effect of smart construction technology characteristics on safety performance is 0.016. The results indicate that in a smart construction environment, the participants’ perceived ease of use, intention to use, and usage behavior play a mediating role in the impact of smart construction technology characteristics on safety performance.

In the path “smart construction technology characteristics–perceived usefulness–intention to use–usage behavior–safety performance”, the indirect effect of smart construction technology characteristics on safety performance is 0.026. Even in situations where the relationship between perceived usefulness and perceived ease of use is not significant, perceived usefulness still plays a crucial role in the impact of smart construction technology characteristics on safety performance. In this study, the total effect of smart construction technology characteristics on safety performance is 0.652, with the impact on individual safety performance being slightly higher than that on project safety performance.

5. Discussion

The findings of this study align with and extend existing research in several meaningful ways. Previous studies have often highlighted the potential of specific smart construction technologies to improve safety outcomes through qualitative analyses [13,14]. However, our study goes beyond these specific technology-focused analyses by providing a comprehensive empirical examination of the broader characteristics of smart construction technologies and their cumulative impact on safety performance. By integrating the technology acceptance model (TAM) and the task–technology fit (TTF) model, our research offers a more holistic view of how these technologies are perceived, adopted, and ultimately influence safety outcomes.

The significant impact of perceived ease of use and perceived usefulness on usage intention found in our study is consistent with the core tenets of the TAM, which posits that these perceptions are key determinants of technology adoption [39]. Perceived usefulness plays a key role in this process. If the characteristics of smart construction technology match its perceived usefulness, then the effective application and promotion of smart construction technology in construction projects are facilitated. Therefore, perceived usefulness, by influencing usage intention and behavior, has a positive impact on project safety performance. Similarly, the characteristics of smart construction technology affect how construction project workers perceive its ease of use. When characteristics such as integration, automation, initiative, shareability, and sustainability are perceived, construction workers are likely to find the technology easy to use and actively engage with it in projects. This, in turn, affects their willingness to use the technology, enhancing project performance through the behavior of using smart construction technology. In these ways, smart construction technology can reduce the incidence of accidents on construction sites because the characteristics of smart construction technology match well with the objectives of construction projects, thereby enhancing project safety performance.

Our findings extend this understanding to the context of smart construction technologies, highlighting the importance of these perceptions in driving usage intentions and actual use in the construction industry. Moreover, the strong positive relationship between usage behavior and safety performance underscores the practical importance of technology adoption. This finding is in line with the work of Azhar et al. [15], who found that the effective use of BIM can lead to significant improvements in project safety. Our study, however, provides a more quantifiable measure of this impact, with a substantial path coefficient of 0.90, indicating a robust relationship between technology use and safety performance.

6. Conclusions and Implications

On the basis of the literature review, this study systematically identified the core characteristics of smart construction technology through expert interviews and factor analysis. By using the TAM and the TTF model, a structural equation model was developed to reveal the effects of smart construction technology characteristics on the safety performance of construction projects. Through a questionnaire survey of personnel in the field of engi-

neering construction in seven provinces in China, 742 sample data were used to test the structural equation model empirically. The conclusions of this study are mainly reflected in two aspects.

First, this study proposes the core characteristics of smart construction technology, namely integration, automation, initiative, shareability, and sustainability. Through analysis and summarization of the existing literature and considering the actual development of the construction industry in China, this study initially identified these core characteristics through expert interviews. A survey was then designed and confirmatory factor analysis was used to pinpoint these five characteristics. The results from the structural equation model indicate that within the characteristics of smart construction technology, shareability (0.42), initiative (0.42), and sustainability (0.49) have a stronger impact than integration (0.39) and automation (0.30). This result suggests that in the implementation of smart construction technology, the applications of shareability, initiative, and sustainability are given more emphasis.

Second, we tested that smart construction technology characteristics have direct and indirect effects on safety performance. Integrating the TAM and the TTF model, this study identified perceived usefulness, perceived ease of use, intention to use, and usage behavior as mediating variables. It proposed pathways through which smart construction technology characteristics impact the safety performance of construction projects and empirically tested these using a structural equation model. The model results show a significant direct impact of smart construction technology characteristics on safety performance, with a direct effect estimate of 0.61. Additionally, smart construction technology characteristics indirectly influence safety performance through perceived ease of use, perceived usefulness, intention to use, and usage behavior, with two indirect paths identified. The influence of perceived usefulness (0.48) is greater than that of perceived ease of use (0.37), suggesting that the characteristics of smart construction technology significantly impact safety performance through their practicality and fit with construction project needs.

This study contributes to the theoretical understanding of the impact of smart construction technologies on safety performance by integrating the TAM and the TTF model. This comprehensive framework links technology characteristics to safety performance through perceived behavior, behavioral intention, and usage behavior. The significant direct and indirect effects observed in this study extend the current literature on technology acceptance and use in the construction industry, highlighting the critical role of technology characteristics in driving safety outcomes. From a practical standpoint, these findings offer valuable insights for construction managers and technology developers. The significant impact of smart construction technology characteristics on perceived ease of use and perceived usefulness suggests that efforts to enhance these characteristics can lead to higher user acceptance and adoption rates. Promoting the ease of use and usefulness of these technologies can foster stronger usage intentions, which in turn can increase actual use. Furthermore, the strong link between usage behavior and safety performance underscores the necessity for training and support systems that encourage frequent and effective use of smart construction technologies. Construction firms should prioritize the implementation and consistent use of these technologies to achieve better safety outcomes.

Despite the robust findings, this study has several limitations. First, this study relies on self-reported data, which may be subject to biases such as social desirability and common method bias. Future studies could incorporate objective measures of technology use and safety performance to validate the findings. Moreover, while this study focuses on five principal characteristics of smart construction technologies, future research could explore additional characteristics and their potential impacts. Investigating the role of organizational culture, management support, and user training in moderating the effects of technology characteristics on safety performance could also provide deeper insights.

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Appendix A

Table A1. Measurement Scale and Factor Analysis.

Variable	Question Item	Load Coef.
IN1	I use a unified office platform and project management system to handle my daily work.	0.885
IN2	Our projects leverage smart construction technology to bring engineering information and data together.	0.922
IN3	Our projects integrate smart construction technologies into a unified platform for use.	0.872
IN4	The office platform between various departments of my project has a sufficient horizontal data summary.	0.878
AU1	I can automatically complete repetitive tasks using electronic devices, such as smartphones, tablets, and computers.	0.911
AU2	With the help of smart construction technology, I can monitor and maintain the status and changes of engineering projects in real time.	0.905
AU3	With the help of smart construction technology, I can fully analyze most of the data on the project.	0.917
AU4	I use smart construction technology to automate processes to save time and energy.	0.962
INI1	Each department of my project can ensure the immediate exchange of information through various communication tools and methods.	0.928
INI2	Smart construction technology allows me to quickly and accurately collect and organize information on my construction site and allows me to obtain the required information and data in real time.	0.885
INI3	Smart construction technology can provide quick decision-making support for my project situation and I rely on this technology to issue control instructions in a timely manner.	0.884
INI4	Smart construction technology can help me predict and control the future development of each part of the project.	0.885
SH1	With the help of online or platform systems, I can assign tasks or issue notifications.	0.886
SH2	In the project I am involved in, smart construction technology enables all participants to stay informed about the project status in a timely manner.	0.948
SH3	The project I am involved in enhances communication efficiency among multiple parties through a unified information or data platform.	0.882
SH4	The information and data collection in my project use unified standards and templates, which can be jointly managed and utilized by multiple participants.	0.882
SU1	The project I am involved in can draw on the experience of smart construction technologies from other projects.	0.928
SU2	The experience I gained using smart construction technologies in previous projects can be applied in upcoming projects.	0.882

Table A1. *Cont.*

Variable	Question Item	Load Coef.
SU3	Smart construction technology is applied throughout the entire lifecycle of my project.	0.863
SU4	My project achieves compliance with green and healthy construction and operation requirements through smart construction technology.	0.867
PU1	Using smart construction technology has improved the quality of my work.	0.884
PU2	Using smart construction technology helps me better manage my work content.	0.807
PU3	Using smart construction technology supports the critical aspects of my work.	0.816
PU4	I find smart construction technology very useful in my work.	0.794
PU5	Using smart construction technology can enhance my work performance.	0.810
PE1	Using smart construction technology does not require many steps.	0.838
PE2	It is easy to acquire smart construction technology for self-protection.	0.871
PE3	Using smart construction technology is easy.	0.933
PE4	I find it easy to make smart construction technology do what I want it to do.	0.846
PE5	Learning to operate smart construction technology is easy for me.	0.854
ITU1	Using smart construction technology is a good idea.	0.923
ITU2	Using smart construction technology is the right choice.	0.823
ITU3	I enjoy using smart construction technology.	0.816
ITU4	Using smart construction technology will be an enjoyable experience.	0.840
ITU5	Assuming I have the opportunity to access smart construction technology, I am inclined to use it.	0.824
ITU6	Given that I have the opportunity to access smart construction technology, I predict I will use it.	0.827
ITU7	If I have the opportunity to access smart construction technology, I would like to use it as much as possible.	0.829
UB1	My project has already started using smart construction technologies.	0.781
UB2	Smart construction technologies are frequently used to solve practical problems and engineering challenges in my project.	0.873
UB3	Various technologies related to smart construction are used in my project, covering a wide range of technology types.	0.794
UB4	Smart construction technologies are used across all departments and throughout all phases of construction in my project, covering a broad scope.	0.802
UB5	The use of smart construction technologies in my project is very frequent, with daily usage.	0.778
UB6	The use of smart construction technologies in my project follows clear standards, and all applications adhere to these standards.	0.816
ISP1	I am aware of my safety responsibilities and the safety management activities that need to be conducted monthly.	0.902
ISP2	Even without supervision, I still complete the safety management tasks required of me within the month on time.	0.781
ISP3	I pay attention to and proactively identify potential safety hazards at the site.	0.737
ISP4	Sometimes, for the sake of convenience at work, I may neglect safety measures.	0.765
ISP5	When a coworker's operation poses a safety risk, I promptly remind them.	0.766
ISP6	When my work is related to safety, I promptly consult with the safety supervision department.	0.772
ISP7	When colleagues point out that my fulfillment of safety responsibilities is inadequate, I accept and correct it.	0.737
ISP8	Sometimes, when unsupervised, I might direct operations improperly for convenience.	0.755
ISP9	In my work, I use all necessary safety protective equipment.	0.763

Table A1. Cont.

Variable	Question Item	Load Coef.
ISP10	In addition to fulfilling my duties, I am also willing to make extra contributions to improve the level of safety management.	0.769
PSP1	When safety conflicts with other issues, safety may be temporarily sacrificed in practice.	0.703
PSP2	When considering promotions for personnel, the company includes safety performance as an important criterion.	0.914
PSP3	Participating in safety education and training is very helpful for my work.	0.787
PSP4	The company provides sufficient resources (such as manpower and funding) to enhance employee safety education.	0.771
PSP5	The safety education provided by the company and the project is guided by practical work.	0.744
PSP6	Employees can easily communicate their safety suggestions to superiors, ensuring smooth communication between both parties.	0.775
PSP7	Inspections and supervision by higher-level units help me improve the project's safety prevention level more effectively.	0.754
PSP8	Higher-level units can communicate effectively and smoothly with employees on safety issues.	0.778
PSP9	My colleagues and I seriously follow the safety regulations issued by higher-level units.	0.752
PSP10	The company's safety policies are formulated after thoroughly consulting with subordinate units and adopting their feedback as an important basis.	0.759

References

- Im, H.J.; Kwon, Y.J.; Kim, S.G.; Kim, Y.K.; Ju, Y.S.; Lee, H.P. The characteristics of fatal occupational injuries in Korea's construction industry, 1997–2004. *Saf. Sci.* **2009**, *47*, 1159–1162. [\[CrossRef\]](#)
- Ringen, K.; Seegal, J.; England, A. Safety and health in the construction industry. *Annu. Rev. Public Health* **1995**, *16*, 165–188. [\[CrossRef\]](#) [\[PubMed\]](#)
- Bilal, M.; Oyedele, L.O.; Qadir, J.; Munir, K.; Akinade, O.O.; Ajayi, S.O.; Akinade, O.O.; Owolabi, H.A.; Alaka, H.A.; Pasha, M. Big data in the construction industry: A review of present status, opportunities, and future trends. *Adv. Eng. Inform.* **2016**, *30*, 500–521. [\[CrossRef\]](#)
- Succar, B.; Kassem, M. Macro-BIM adoption: Conceptual structures. *Autom. Constr.* **2015**, *57*, 64–79. [\[CrossRef\]](#)
- Navon, R.; Goldschmidt, E. Monitoring labor inputs: Automated-data-collection model and enabling technologies. *Autom. Constr.* **2003**, *12*, 185–199. [\[CrossRef\]](#)
- Newaz, M.T.; Ershadi, M.; Carothers, L.; Jefferies, M.; Davis, P. A review and assessment of technologies for addressing the risk of falling from height on construction sites. *Saf. Sci.* **2022**, *147*, 105618. [\[CrossRef\]](#)
- Ali, M.; Aziz, S.; Pham, T.N.; Babalola, M.T.; Usman, M. A positive human health perspective on how spiritual leadership weaves its influence on employee safety performance: The role of harmonious safety passion. *Saf. Sci.* **2020**, *131*, 104923. [\[CrossRef\]](#)
- Chung, W.W.S.; Tariq, S.; Mohandes, S.R.; Zayed, T. IoT-based application for construction site safety monitoring. *Int. J. Constr. Manag.* **2023**, *23*, 58–74. [\[CrossRef\]](#)
- Zhang, S.; Sulankivi, K.; Kiviniemi, M.; Romo, I.; Eastman, C.M.; Teizer, J. BIM-based fall hazard identification and prevention in construction safety planning. *Saf. Sci.* **2015**, *72*, 31–45. [\[CrossRef\]](#)
- Matthews, J.; Love, P.E.; Heinemann, S.; Chandler, R.; Rumsey, C.; Olatunj, O. Real time progress management: Re-engineering processes for cloud-based BIM in construction. *Autom. Constr.* **2015**, *58*, 38–47. [\[CrossRef\]](#)
- Hao, M.; Nie, Y. Hazard identification, risk assessment and management of industrial system: Process safety in mining industry. *Saf. Sci.* **2022**, *154*, 105863. [\[CrossRef\]](#)
- Dokas, I.M.; Feehan, J.; Imran, S. EWaSAP: An early warning sign identification approach based on a systemic hazard analysis. *Saf. Sci.* **2013**, *58*, 11–26. [\[CrossRef\]](#)
- Li, H.; Lu, M.; Hsu, S.C.; Gray, M.; Huang, T. Proactive behavior-based safety management for construction safety improvement. *Saf. Sci.* **2015**, *75*, 107–117. [\[CrossRef\]](#)
- Zhang, S.; Teizer, J.; Lee, J.K.; Eastman, C.M.; Venugopal, M. Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules. *Autom. Constr.* **2013**, *29*, 183–195. [\[CrossRef\]](#)
- Afzal, M.; Shafiq, M.T. Evaluating 4D-BIM and VR for effective safety communication and training: A case study of multilingual construction job-site crew. *Buildings* **2021**, *11*, 319. [\[CrossRef\]](#)
- Edirisinghe, R. Digital skin of the construction site: Smart sensor technologies towards the future smart construction site. *Eng. Constr. Archit. Manag.* **2019**, *26*, 184–223. [\[CrossRef\]](#)

17. Eastman, C.; Teicholz, P.; Sacks, R.; Liston, K. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
18. Love, P.E.D.; Matthews, J.; Simpson, I.; Hill, A.; Olatunji, O. A benefits realization management building information modeling framework for asset owners. *Autom. Constr.* **2012**, *37*, 1–10. [\[CrossRef\]](#)
19. Wang, X.; Love, P.E.D.; Kim, M.J.; Park, C.S. A conceptual framework for integrating building information modeling with augmented reality. *Autom. Constr.* **2014**, *44*, 76–84. [\[CrossRef\]](#)
20. Boje, C.; Guerriero, A.; Kubicki, S.; Rezgui, Y. Towards a semantic Construction Digital Twin: Directions for future research. *Autom. Constr.* **2020**, *114*, 103179. [\[CrossRef\]](#)
21. Nelson, R.R.; Todd, P.A.; Wixom, B.H. Antecedents of information and system quality: An empirical examination within the context of data warehousing. *J. Manag. Inf. Syst.* **2005**, *21*, 199–235. [\[CrossRef\]](#)
22. Kerimoglu, O.; Basoglu, N.; Daim, T. Organizational adoption of information technologies: Case of enterprise resource planning systems. *J. High Technol. Manag. Res.* **2008**, *19*, 21–35. [\[CrossRef\]](#)
23. Abugabab, A.; Sanzogni, L.; Poropat, A. *The Impact of Information Systems on User Performance: A Critical Review and Theoretical Model*; World Academy of Science, Engineering and Technology (WASET): Paris, France, 2009; pp. 809–819.
24. Fathi, M.S.; Abedi, M.; Rambat, S.; Rawai, S.; Zakiyudin, M.Z. Context-aware cloud computing for construction collaboration. *J. Cloud Comput.* **2012**, *2012*, 644927. [\[CrossRef\]](#)
25. Štefanič, M.; Stankovski, V. A review of technologies and applications for smart construction. *Proc. Inst. Civ. Eng.-Civ. Eng.* **2018**, *172*, 83–87. [\[CrossRef\]](#)
26. Kang, Y.; O'Brien, W.J.; Thomas, S.; Chapman, R.E. Impact of information technologies on performance: Cross study comparison. *J. Constr. Eng. Manag.* **2008**, *134*, 852–863. [\[CrossRef\]](#)
27. Ahn, T.; Ryu, S.; Han, I. The impact of the online and offline features on the user acceptance of Internet shopping malls. *Electron. Commer. Res. Appl.* **2004**, *3*, 405–420. [\[CrossRef\]](#)
28. Shan, Y.; Goodrum, P.M.; Zhai, D.; Haas, C.; Caldas, C.H. The impact of management practices on mechanical construction productivity. *Constr. Manag. Econ.* **2011**, *29*, 305–316. [\[CrossRef\]](#)
29. Jing, X.; Zhang, L.; Feng, X.; Sun, B.; Li, Q. A novel bio-inspired anti-vibration structure for operating hand-held jackhammers. *Mech. Syst. Signal Process.* **2019**, *118*, 317–339. [\[CrossRef\]](#)
30. Porwal, A.; Hewage, K.N. Building Information Modeling (BIM) partnering framework for public construction projects. *Autom. Constr.* **2013**, *31*, 204–214. [\[CrossRef\]](#)
31. Fu, X.; Wu, M.; Tiong, R.L.K.; Zhang, L. Data-driven real-time advanced geological prediction in tunnel construction using a hybrid deep learning approach. *Autom. Constr.* **2023**, *146*, 104672. [\[CrossRef\]](#)
32. Sanhudo, L.; Ramos, N.M.; Martins, J.P.; Almeida, R.M.; Barreira, E.; Simões, M.L.; Cardoso, V. Building information modeling for energy retrofitting—A review. *Renew. Sustain. Energy Rev.* **2018**, *89*, 249–260. [\[CrossRef\]](#)
33. Becerik-Gerber, B.; Jazizadeh, F.; Li, N.; Calis, G. Application of BIM and IT for high performance integrated project delivery. *J. Constr. Eng. Manag.* **2012**, *138*, 95–104.
34. Park, J.Y.; Lee, D.Y.; Kim, S.K.; Kwon, S.W. A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template. *Autom. Constr.* **2011**, *33*, 61–71. [\[CrossRef\]](#)
35. Gong, J.; Caldas, C.H. Computer vision-based video interpretation model for automated productivity analysis of construction operations. *J. Comput. Civ. Eng.* **2010**, *24*, 252–263. [\[CrossRef\]](#)
36. Huber, G.P. A theory of the effects of advanced information technologies on organizational design, intelligence, and decision making. In *Knowledge, Groupware and the Internet*; Routledge: London, UK, 2009; pp. 221–254.
37. Sproull, L.; Kiesler, S. Reducing social context cues: Electronic mail in organizational communication. *Manag. Sci.* **1986**, *32*, 1492–1512. [\[CrossRef\]](#)
38. Igbaria, M.; Tan, M. The consequences of information technology acceptance on subsequent individual performance. *Inf. Manag.* **1997**, *32*, 113–121. [\[CrossRef\]](#)
39. Davis, F.D. Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Q.* **1989**, *13*, 319–340. [\[CrossRef\]](#)
40. Venkatesh, V. Where to go from here? Thoughts on future directions for research on individual-level technology adoption with a focus on decision making. *Decis. Sci.* **2006**, *37*, 497–518. [\[CrossRef\]](#)
41. Ahearne, M.; Jones, E.; Rapp, A.; Mathieu, J. High touch through high tech: The impact of salesperson technology usage on sales performance via mediating mechanisms. *Manag. Sci.* **2008**, *54*, 671–685. [\[CrossRef\]](#)
42. Goodhue, D.L.; Thompson, R.L. Task-technology fit and individual performance. *MIS Q.* **1995**, *19*, 213–236. [\[CrossRef\]](#)
43. Goodhue, D.L. Development and measurement validity of a task-technology fit instrument for user evaluations of information system. *Decis. Sci.* **1998**, *29*, 105–138. [\[CrossRef\]](#)
44. Dishaw, M.T.; Strong, D.M. Supporting software maintenance with software engineering tools: A computed task–technology fit analysis. *J. Syst. Softw.* **1998**, *44*, 107–120. [\[CrossRef\]](#)
45. Kloppping, I.M.; McKinney, E. Extending the technology acceptance model and the task-technology fit model to consumer e-commerce. *Inf. Technol. Learn. Perform. J.* **2004**, *22*, 35–48.
46. Klaus, T.; Gyires, T.; Joseph Wen, H. The use of web-based information systems for non-work activities: An empirical study. *Hum. Syst. Manag.* **2003**, *22*, 105–114. [\[CrossRef\]](#)

47. Yen, D.C.; Wu, C.S.; Cheng, F.F.; Huang, Y.W. Determinants of users' intention to adopt wireless technology: An empirical study by integrating TTF with TAM. *Comput. Hum. Behav.* **2010**, *26*, 906–915. [[CrossRef](#)]
48. Marcolin, B.L.; Compeau, D.R.; Munro, M.C.; Huff, S.L. Assessing user competence: Conceptualization and measurement. *Inf. Syst. Res.* **2000**, *11*, 37–60. [[CrossRef](#)]
49. Dennis, A.R.; Wixom, B.H.; Vandenberg, R.J. Understanding fit and appropriation effects in group support systems via meta-analysis. *MIS Q.* **2001**, *25*, 167–193. [[CrossRef](#)]
50. Devaraj, S.; Kohli, R. Performance impacts of information technology: Is actual usage the missing link? *Manag. Sci.* **2003**, *49*, 273–289. [[CrossRef](#)]
51. Fang, Y.C.; Dzeng, R.J. Accelerometer-based fall-potential detection algorithm for construction tiling operation. *Autom. Constr.* **2017**, *84*, 214–230. [[CrossRef](#)]
52. Al-Bayati, A.J.; Karakhan, A.A. Annual Revenue's Influence on the Safety Performance of Construction Firms. In *Construction Research Congress 2022: Health and Safety, Workforce, and Education, Proceedings of the Construction Research Congress 2022, Arlington, VA, USA, 9–12 March 2022*; American Society of Civil Engineers: Reston, VA, USA, 2022; pp. 386–392.
53. Selleck, R.; Hassall, M.; Cattani, M. Determining the reliability of critical controls in construction projects. *Safety* **2022**, *8*, 64. [[CrossRef](#)]
54. Man, S.S.; Alabdulkarim, S.; Chan, A.H.S.; Zhang, T. The acceptance of personal protective equipment among Hong Kong construction workers: An integration of technology acceptance model and theory of planned behavior with risk perception and safety climate. *J. Saf. Res.* **2021**, *79*, 329–340. [[CrossRef](#)]
55. Ayikoru, M.; Ddamulira, C.; Mutekanga, D.R. Determinants of employee use of personal protective equipment, the case of Spedag Interfreight Uganda limited, Kampala. *J. Environ. Sci. Public Health* **2019**, *3*, 419–434. [[CrossRef](#)]
56. Izudi, J.; Ninsiima, V.; Alege, J.B. Use of personal protective equipment among building construction workers in Kampala, Uganda. *J. Environ. Public Health* **2017**, *2017*, 7930589. [[CrossRef](#)] [[PubMed](#)]
57. Sanni-Anibire, M.O.; Mahmoud, A.S.; Hassanain, M.A.; Salami, B.A. A risk assessment approach for enhancing construction safety performance. *Saf. Sci.* **2020**, *121*, 15–29. [[CrossRef](#)]
58. Xu, J.; Cheung, C.; Manu, P.; Ejohwomu, O.; Too, J. Implementing safety leading indicators in construction: Toward a proactive approach to safety management. *Saf. Sci.* **2023**, *157*, 105929. [[CrossRef](#)]
59. Oh, H.K.; Kim, T.S. Factors affecting an organization's information security performance: The characteristics of information security officers. In *Big Data Analyses, Services, and Smart Data, Proceedings of the Sixth International Conference on Big Data Applications and Services (BigDAS 2018), Zhengzhou, China, 19–22 August 2018*; Springer: Singapore, 2021; pp. 77–84.
60. Wong, T.K.M.; Man, S.S.; Chan, A.H.S. Critical factors for the use or non-use of personal protective equipment amongst construction workers. *Saf. Sci.* **2020**, *126*, 104663. [[CrossRef](#)]
61. Kang, L.; Wu, C.; Liao, X.; Wang, B. Safety performance and technology heterogeneity in China's provincial construction industry. *Saf. Sci.* **2020**, *121*, 83–92. [[CrossRef](#)]

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