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Theoretical Models for Evaluating and Predicting the Diffusion of Safety Technologies in Construction

Chukwuma Nnaji, Ph.D.
Texas A&M University
College Station, Texas

Ibukun Awolusi, Ph.D.
The University of Texas as San Antonio
San Antonio, Texas

Several studies have investigated the benefits of applying emerging technologies in the construction industry, but information about how these technologies can be successfully implemented in construction, particularly for safety management is limited. Different theories and frameworks have been posited and successfully implemented in different industries. However, a detailed exploration of the utility of these frameworks within the context of construction safety management is missing. The main purpose of this research is to synthesize available information on different applicable theoretical models for evaluating and predicting the diffusion of safety technologies in construction. Using an integrated review process, the authors evaluated 12 promising theories and models that are rarely utilized in construction research. Potential applications, strengths, and limitations are discussed herein. The results of the review are used to propose multiple theoretical models that could be utilized to better understand and predict the diffusion of safety technologies in the construction industry. This study reveals the key factors, within multiple frameworks, that affect the adoption, adaptation, and infusion of technologies for safety management in construction. Practitioners and researchers could utilize information from this study to evaluate the diffusion of specific technologies within an organization and the construction industry.

Keywords: Construction Safety, Decision Support, Diffusion, Explanatory Model, Predictive Model, Safety Technology, Theoretical Model.

Introduction

The construction industry is known to be highly fragmented with the work environment characterized by different levels of operations within the project, organization, and across the industry (Hu et al., 2019). Although the use of technologies in the construction industry has shown some potential to improve work performance, research studies suggest that the industry still suffers pushback from employees (Wang et al., 2020). Hence, the examination of end-user behavior, and the use and impact of technologies to encourage extended use is very crucial before deciding to invest significantly in a technology (Jin et al. 2019). The quest to salvage this situation has prompted researchers to continuously investigate factors critical to successful technology integration (Darko et al., 2017) using explanatory and predictive theories and models which have proven to be effective in information systems research (Chin et al., 2020; Tarhini et al., 2015; Taherdoost, 2018; Okpala et al., 2022). To provide research direction into the technology adoption process and potential research areas, Sepasgozar et al. (2016)

reviewed construction technology adoption in the construction industry, with an emphasis on equipment utility and information flow. Like Sepasgozar et al. (2021), the proposed conceptual models developed centered on the adoption of subprocesses and modeling-specific technologies (mixed reality and digital twin). These models allow for (1) explanatory modeling, the establishment of causal relationships between technology acceptance/use and factors attributed to individual workers, technologies, and environmental factors, and (2) predictive modeling which is the determination of the combination of adoption factors that best predict technology use (Sainani, 2014).

Although construction researchers have been utilizing these theories and models to gain insight into factors that explain and predict different types of technologies used within the sector, there is no domain-specific synthesis on how these theories and models can be used as tools to facilitate the integration of emerging construction technologies. Conversely, other sectors, such as healthcare (Omachonu & Einspruch, 2010) and manufacturing (Taherdoost, 2018), have conducted several syntheses on these theories and models, and have developed contextual insight geared toward guiding future research and development. Therefore, this paper synthesizes available information on different applicable theoretical models for evaluating and predicting the diffusion of technologies for safety and health management in construction.

Literature Review

Technological Innovation and Use in Construction

The project-based nature, constant need for collaboration, inter-organizational activities, power distribution in practice, and established avenues for communication and data sharing (Harty, 2008) make the construction industry is unique and complex sector. Although these special attributes have made innovation and other industry transformations an uphill task (Green, 2011), researchers and practitioners have continued to pursue the development and implementation of technological solutions to continuously enhance work output (Sherratt et al., 2020). The level of saturation attained in the use of traditional work programs to improve key project success factors also makes a strong case for the need to increase technological innovation research and application in construction (Esmaeili & Hallowell, 2012). When compared to other industries, innovation integration and productivity rates within construction are relatively low (Ozorhon, 2013) thus, emphasizing the need for more research studies in this area (Liu & Liu, 2017).

A number of studies have discussed technology applications in different areas of construction management including safety and health management (Okpala et al., 2020), performance and productivity (Kim et al., 2019), cost (Martínez-Rojas et al., 2016), schedule (Uusitalo et al., 2017), and quality (El-Omari & Moselhi, 2011; Ogunrinde et al., 2020). The different categories of technologies discussed in these studies include enhanced information technologies, geospatial technologies, imaging technologies (photogrammetry and laser scanning), immersive visualization technologies (Building information modeling, augmented reality, and virtual reality), robotics and automation, and wearable technologies (Awolusi et al., 2018; Choi et al., 2017; Shen et al., 2017). Despite the potential of these technologies to positively impact workers and project performance within construction, their integration and diffusion still fall behind (Chen et al., 2020). To enhance the technology integration process (TIP) for existing and emerging technologies, a proper understanding of phases is essential to the successful integration of innovation into a new environment.

Technology adoption and integration occur at four levels – individual, project, organization, and industry level. In holistically assessing the status quo in technology integration, researchers have explored innovation frameworks incorporating industry-specific drivers, enablers, and barriers to innovation integration industry-wide (Owolabi et al., 2019), organizational/firm-level (Slaughter, 2000), project level (Ozorhon et al., 2016), and the individual level (Choi et al., 2017). To successfully integrate technology in the construction sector, there is a need for a hybrid (top-down and bottom-up) adoption approach that accounts for factors (drivers, barriers, and enablers) impacting all levels (Nnaji et al., 2019). Predictive and explanatory models rely on these factors to deliver realistic and significant contextual information on potential adoption and acceptance.

Predictive and Explanatory Technology Integration Modeling

Technology integration models and theories are analyzed and operationalized using predictive and explanatory modeling processes (Shmueli & Koppius, 2011). Valuable outputs have been reported within the past decades about the prediction and explanation of factors that impact technology adoption at different levels in the construction domain (Tarhini et al., 2015). Explanatory modeling is focused on evaluating the causal relationships between constructs (portraying individuals, a project, or an organization), while predictive modeling deals with the forecasting of an end construct made possible by a combination of independent adoption factors (Sainani, 2014). In order to correctly explain technology acceptance (behavioral intention or actual use) using independent variables (causal influences), the prediction must be accurate (Abbasi et al., 2015) because inaccurate predictions could lead to suspect decision-making, resulting in a failed TIP. Within the last four decades, researchers in the information systems research domain have developed multiple models and theories for explaining and predicting user adoption and acceptance (Davis, 1989). At the individual level, researchers have repeatedly and satisfactorily used the Technology Acceptance Model (TAM) (Davis, 1989; Davis et al., 1989; Lee et al., 2015), the Theory of Planned Behaviour (TPB) (Ajzen, 1991; Liu, 2020), and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Okpala et al., 2022; Williams et al., 2015; Venkatesh et al., 2003) in modeling technology and system-based acceptance using a variety of technology attributes and contextual factors (Rahman et al., 2017).

The TAM is made up of key acceptance constructs: Perceived Usefulness (PU), Perceived Ease of Use (PEU), Attitude (ATT), Behavioural Intention to Use (BI), and Actual Use (Davis et al., 1989), with behavioral intention being the measure of actual technology use (Davis et al., 1989). The UTAUT incorporates “facilitating conditions,” a new construct which when with the other four constructs, Performance Expectancy (PE), Behaviour and Actual Behaviour (Actual Use), Effort Expectancy (EE), and Social Influence (SI) (Venkatesh et al., 2003), capture workers’ perception of availability of internal and external resources necessary for using a new technology (Tao et al., 2020). Other existing predictive and explanatory models which can be utilized in construction include the Theory of Reasoned Action (TRA), the extended TAM (TAM2), the Task-technology fit model, the Motivational Model, the Diffusion of Innovation Theory, PESTEL analysis, the Technology-Organization-Environment model, Explanation-confirmation Model, change and knowledge management theory, MITE (management, individual, technology, and environment), and Social Cognitive (Tarhini et al., 2015).

Research Method

This study presents an integrated review of the use of predictive and explanatory models in construction technology integration research. A mainstream paper database, Scopus, was utilized (Ayodele et al., 2020) to source relevant publications. These databases have the reputation of housing comprehensive information (title, abstract, citation, and keywords) of articles directly sourced from major building, construction, innovation, and project management journals (Hu et al., 2019). The authors searched for articles within Scopus using relevant keywords/keyphrases appropriately combined. The keywords included Construction AND (technology acceptance OR technology adoption OR model OR theory OR path analysis OR structural equation modeling OR regression OR project OR organization OR industry OR explanatory modeling OR predictive modeling OR construction management OR variables OR constructs OR confirmatory factor analysis OR regression analysis). The initial database search yielded 233 articles. In selecting and filtering the identified publications, the authors utilized several important criteria such as publication basic information, subject areas, etc., to assess the research papers for eligibility (Hu et al., 2019). A total of 109 articles were included for quality assessment and 35 out of those were included in this review, thus excluding 74 papers that did not meet the established criteria for this study.

The content of selected articles was analyzed in detail to 1) establish a description of the articles alongside their journal sources, publication year, and the spread by articles' country of origin; 2) trend different methods and theories used for predicting technology adoption and acceptance, and; 3) develop insight to guide the quality of future studies on forecasting technological applications in construction. Content analysis, as a research technique, has been utilized in multiple fields, and for determining major themes, trends, and other qualitative and quantitative metrics derived from messages (written, verbal, or visual), and depending on the project research problem to be solved (Siraj & Fayek, 2019).

Findings and Discussion

Predicting Technology Adoption and Acceptance in Construction

An evaluation of the existing theories and models utilized in construction technology integration research shows that TAM stands out as the primary basis for explaining acceptance and predicting acceptance. A visible trend exists in which researchers move to optimize the base models to ensure that the measurement model closely represents real-life construction situations (Lee et al. 2015). For example, Choi et al. (2017) introduced the “Perceived Privacy Risk” construct to evaluate workers’ concerns regarding the handling of personal information in the use of wearable technologies. Table 1 presents a summary of information (e.g., technology investigated, countries, and the primary application of the models) from some independent studies about acceptance theories and models in construction technology research.

As seen in Table 1, Building Information Modelling (BIM) stands out as the technology commonly investigated, followed by wearable technologies (WT), enterprise resource planning (ERP) systems, augmented reality (AR), and other smart construction systems (SCS) such as robotics and mobile computing (MC). Others investigated include information and communications technology (ICT), online project information management system (OPIMS), remotely piloted aircraft (RPA), Building Management Systems (BMS), Web-based Training (WBT), and prefabrication. This could be attributed to the high industry acceptance level of BIM when compared to other technologies or systems (Son et al., 2012), hence, the need to further investigate workers’ perceptions from different schools of thought. Most studies sampled construction practitioners and utilized data obtained to test measurement models and obtain insights critical to understanding the behavioral intention to use a technology, and actual use (Lee & Yu, 2017). In addition, when closely looking at the primary applications of the technology, there is a healthy mix between the individual, project, organization, and industry-level scenarios. The choice of which level of application is largely dependent on the researchers’ project direction hence, currently, the authors found some precursors for the future choice of technological primary application focus. It is necessary to state that a number of existing technologies tested as presented in the Table (BIM, ICT tools, MC; RPA) are well past the development stage (Chen et al., 2020; Choi et al., 2017) and have begun to find increased construction use. This explains the absence of technologies like artificial intelligence, wearable robotics, single-task construction robots, and other emerging technologies that are still being developed and optimized for productive construction use.

Table 1
Acceptance Theories and Models in Construction Technology Research

Theory/Model	Technology	Country	Application
TAM	BIM, WT, SCS, OPIMS, ICT, AR, ERP, BMS, Prefab, ICA	South Korea, USA, China, Ghana, Australia, Peru, Malaysia, United Kingdom, Norway, Netherlands	Individual, Projects, Organization, Industry.
TAM2	WBT, WT, BIM, ICT, ERP, SCS	South Korea, USA,	Individual, Project, Organization, Industry.
TAM3	BIM	South Korea	Organization
D&M model	WT, BIM, ERP	USA, South Korea	Project, Organization, Industry
TPB	WT, BIM, ICT	USA, South Korea, Netherlands	Organization, Industry
IDT	BIM	South Korea, China	Project, Industry
UTAUT	WT, BIM, ICT	USA, South Korea, United Kingdom, Peru, Netherlands, Australia	Individual, Project, Organization, Industry
Equity Theory	BIM	China	Project
ECM	BIM	China	Individual
TTF	BIM, RPA	South Korea, Australia	Project, Organization
DOI	OPIMS	Australia	Industry

Constructs Influencing Construction Technology Acceptance Decisions

The findings of the review process show that the Technology Acceptance Model (TAM), extended-TAM, UTAUT, Diffusion of Innovation Theory (IDT), Expectation-confirmation model (ECM), Task Technology Fit (TTF), and the DeLone and McLean IS Success Model have been utilized as a stand-alone model, in combination with other models, or as a fundamental framework for the conceptualization of novel models to explain or predict technology acceptance. The critical constructs and their respective models which commonly contain the constructs are shown in Table 2. The data presented in Table 2 highlight key constructs that construction researchers believe impact technology acceptance decisions indicating that these constructs will most likely be commonly used in future studies. For instance, it could be very critical to test if or not individual users think a new technology is useful (perceived usefulness) and easily operatable (perceived ease of use). Moreover, if workers think the work environment (facilitating conditions) enables them to productively use the new technology, additional critical insights on whether they intend to use the technology (Behavioural Intention) or to continue using the technology (Actual Use) may need to be generated. From the studies accessed, commonly considered moderators include gender, age, experience, project size, and project type (Wang et al. 2020; Aroke et al., 2022). The authors believe that researchers and practitioners must understand intrinsic population characteristics which can affect the outcomes of quantitative analyses aimed at predicting technology integration.

The performance of models was also evaluated to determine which models currently stand out as high-performing models in terms of ability to explain total variance or predictive power. The results indicate that the Technology Acceptance Model and the Unified Theory of Acceptance and Use of Technology (UTAUT) outperform other models and theories in terms of the predictive power of the behavioral intention to use a new technology. The weaker models identified in the present study are conceptual hybrid models that incorporate TAM and other theories such as Innovation Diffusion and Equity Theories.

Table 2
Constructs Influencing Construction Technology Acceptance Decisions

Constructs	Definition	Theory/Model
Perceived Usefulness (PU); Performance Expectancy (PE)	The extent of individual belief regarding how the use of a particular technology will enhance work performance.	TAM, TPB, TAM2, UTAUT
Perceived Ease of Use (PEU); Effort Expectancy (EE)	The extent of individual belief regarding how the use of a particular technology would be free of effort.	TAM, TAM2, UTAUT
Subjective Norm (SN); Social Influence (SI)	The extent to which an individual thinks that it is vital that others should utilize the new technology.	TPB, TAM2, UTAUT
Behavioral Intention (BI)	An estimate of the strength of an individual's intention to act in a specified way.	TAM, TPB, TAM2, UTAUT
Actual usage Behavior (AU)	The actual behavior of people using a system.	TAM, TPB, TAM2, UTAUT
Attitude (ATT)	An individual's specific beliefs and degree of emotional attraction toward a system.	TAM, TPB
Perceived Behavioural Control (PBC)	The perceived ease or difficulty of an individual acting in a specified way.	TPB
Facilitating Conditions (FC)	Environmental factors designed to make an act easy to be carried out.	UTAUT

Conclusion and Further Research

Technology acceptance theories and models are under-researched in the construction domain compared to other sectors like health, information systems, education, and manufacturing. However, few studies on technology acceptance have been performed across the globe and published in top journals with only a few technologies and application schemes being sufficiently explored. There is a need for a more comprehensive reach and the influx of systematic studies that could be assisted by insights developed in the present study. To facilitate construction technology adoption, it is imperative that researchers keep exploring the use of technology integration modeling at all levels (individual, project, organizational, and industry levels) and across different integration phases. For some studies, the model could contain different sub-domain characteristics. These explanatory and predictive models and theories can find very productive applications as decision-support tools in construction organizations ready to explore and possibly adopt novel work strategies and technological advancement. It is also important to preserve and continue seeking ways to improve upon existing quantitative predictive and explorative modeling methods.

Technology integration has become pertinent in the push for significant improvements in the construction sector in terms of productivity, safety, cost and schedule, and quality. To achieve this improvement, there is a pressing need for construction researchers and practitioners to work towards the development, optimization, and usage of empirical tools to foster the effective integration of technologies into construction operations. This effort requires a proper understanding of factors that influence the behavioral intention to the use, and actual usage of construction technologies. Using a systematic review, this study has summarized the current state of development and usage of explanatory and predictive tools to forecast technology acceptance. This study contributes to knowledge and practice in construction by 1) systematically reviewing the body of knowledge about the models and theories used for technology integration research in construction thus, providing critical case studies for practitioners, and laying a solid foundation for the onward study of the subject by researchers; 2) evaluating the specific factors that predict the adoption and acceptance of technologies in construction research thus allowing for an expanded understanding of construction practitioners inherent behaviors critical to decision-making, and; (3) developing critical insight needed to guide the quality of future studies on forecasting technological applications in construction practice.

However, this study has a few limitations some of which are common to most review studies. For instance, a few relevant articles could have been inadvertently missed even with the fact that a systematic process was followed to identify useful papers within the scope of the study. In addition, this study limited the sources of information to journal papers using an established criterion and did not consider conference papers, reports, and online materials that could provide more insights into technology acceptance. In spite of these identified limitations, this study contributes to an incisive understanding of the current state of the technology integration process in the construction industry.

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