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Business model innovation as a mediator between construction 4.0 and firm performance: Evidence from Turkish construction companies

Omimah Alsaadi [a,*], Lutfihak Alpkan [b], Bora Yildiz [c]

[a] Istanbul Technical University, Graduate School, Department of Management, İTÜ Ayazaga Campus, Maslak, 34469, Istanbul, Turkey
[b] Istanbul Technical University, Faculty of Management, Department of Management, Maçka, Beşiktaş, 34330, İstanbul, Turkey
[c] Istanbul University, Faculty of Economics, Department of Management, Beyazit-Fatih, 34197, Istanbul, Turkey

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ABSTRACT

The construction industry has a crucial place in any country's economy. However, compared to other sectors, construction companies have been relatively slow to adopt new technologies, while most companies in different sectors have already begun to adopt the latest technologies to renovate their way of doing business and improve their overall performance. Therefore, Construction 4.0, as the digital transformation of construction companies in the era of Industry 4.0, attracts the attention of both practitioners and researchers. This empirical study aims to uncover the complex relations among Construction 4.0, Business Model Innovation (BMI), and firm performance in a developing country context. We propose an original model of relations purporting that BMI mediates the positive effects of Construction 4.0 on firm performance, drawing mainly on the dynamic capabilities view. All statistical analyses were performed by using R statistical language. Data was gathered from 152 managers in the Turkish construction sector via the convenience sampling method. Descriptive statistics, validity, reliability, correlation, and PROCESS mediation analyses were used to test research hypotheses. The results show that both digital and physical layers of Construction 4.0 positively relate to firm performance and that BMI fully mediates this positive relation. Managerial and further research implications are forwarded.

1. Introduction

Digital transformation is spreading rapidly in most business sectors, from services to manufacturing, to increase and sustain organizational performance. In this sense, the possible performance outcomes of the adoption and use of technologies have recently become an important area of interest for both researchers and practitioners; this has also led managers to be eager and sensitive to invest more in this transformation to keep their organization up to date (e.g., Hassoun et al., 2022; Bianchini et al., 2022). However, some sectors, such as construction and agriculture, are very slow to adapt to new technologies compared to others, e.g., media, finance, manufacturing, etc. Especially, the construction sector seems reluctant to adopt the latest technologies and, in turn, innovation (Elmualim and Gilder, 2014), given the close relationship between technological improvements and innovation (Rajapathirana and Hui, 2018). Although the general investments in this sector are rapidly growing, estimated to be around $14 trillion by 2025,

* Corresponding author.
E-mail addresses: alsaadi@itu.edu.tr (O. Alsaadi), alpkan@itu.edu.tr (L. Alpkan), borayildiz@istanbul.edu.tr (B. Yildiz).

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contributing to more than 13% of the global GDP (e.g., Gerbert et al., 2016; Rastogi, 2017; McKinsey, 2017; McKinsey, 2020), the awareness of the need to develop digitalization and to invest accordingly in newer technologies has been relatively slow. In addition, the construction sector in developing economies is more stuck in traditional practices and sluggish in adopting digital technologies (Oke et al., 2024).

The future transformation of the construction sector is crucial for developing countries, especially because it plays a vital role not only in their technological and socioeconomic development but also in the growth of their international competitive power. For instance, China, as an emerging economy, is the leader of the global construction market, while the Turkish construction sector, as an essential driving force of the national economy (Globaldata, 2023), holds second place in the international markets in terms of the number of companies within the list of top 250 global contractors (ENR, 2022; Palabiyik, 2022). A recent sectoral SWOT analysis in Türkiye indicates that there are huge opportunities, specifically in the domain of smart technologies, to differentiate in the highly competitive global marketplace, and large Turkish construction companies are relatively strong in terms of general technological investments already done. According to this analysis, while efforts for institutionalization and branding are limited and financial investment costs are not always very suitable, investments in advanced technologies are growing, and those investments to be done in smart technologies may provide newer opportunities to innovate and differentiate soon (Çetinsaya, 2020).

"Construction 4.0", as the integration of Industry 4.0 into the construction sector, has gained the interest of practitioners and researchers, especially in developed countries within the last ten years. However, in the construction sector of especially developing countries, acceptance of these novel technologies and approaches seems to be slower because of managerial concerns related to the ability and/or reluctance to reconfigure the technological infrastructure and renovate the present business model without any degradation of performance. In this concern, empirical studies on the organizational efforts in adopting digital technologies and their effects on BMI and firm performance are still limited. New studies are needed in the context of the traditional sectors of developing countries. Therefore, this empirical study concentrates particularly on survey data that we collected from Turkish construction companies to examine the effects of both digital and physical layers of Construction 4.0 technologies on BMI and firm performance in a developing country context to answer the following research questions:

- *RQ1. How does the digital layer of Construction 4.0 relate to BMI and firm performance in the construction sector in a developing country context?*
- *RQ2. How does the physical layer of Construction 4.0 relate to BMI and firm performance in the construction sector in a developing country context?*

2. Literature review

2.1. Theoretical background

Drivers of innovation and sustainable firm performance with specific reference to BMI have been studied for decades in the learning school of the strategic management literature since strategic learning is one of the critical abilities behind innovative achievementsAlpkan et al., 2021). Towards the end of the last century, the most critical source of sustainable competitive advantage was the organizational "ability to learn" faster than competitors by contributing to the emergence of some unique combinations of organizational skills to be utilized in developing new products and entering new markets (de Geus, 1988). In this concern, organizational capabilities need to be dynamic to reshape competition by integrating, building, and reconfiguring competencies, addressing rapidly changing environments, and then achieving innovative forms of competitive advantage (Teece et al., 1997). This dynamism necessitates successful management of strategic reconfigurations by redesigning the organizational structure itself (before other innovations) to better serve the creation and capture of the intended value proposition (Galbraith et al., 2002). In other words, for better innovative performance, by continuously learning from mistakes and earlier experiences, the whole model of doing business, i.e. organizational systems, processes, value propositions, etc., needs to be reconfigured in a formalized, harmonized and dynamic way not only to adapt but also to reshape or disrupt the competition (Alpkan and Doğan, 2008). Therefore, BMI, especially since the beginning of this century, has become central to the sustainable competitive advantage. Chesbrough (2010) states that those firms capable of making BMI can successfully transfer their novel inputs (e.g., creative ideas, technological investments, newer processes, etc.) to better commercial value than competitors having similar inputs. In this concern, such dynamically capable organizations will be able to rapidly implement, test, and refine new and revised business models by allowing the company's internal IT resources to be focused on more important activities, such as digitizing an existing business or crafting new digital business models (Teece, 2018). Then, in a recent article, Teece (2020) develops a comprehensive perspective about the foundations of long-term competitive advantage of the business enterprise where managerial decisions and firm capabilities should align with new technological opportunities (e.g. digital and/or physical technological developments, market demand for new technologies, etc.) and related innovation systems and regulations.

2.2. Firm performance

Appraising if the firm and its operations are getting more effective and efficient than before and when compared to competitors is necessary for business survival. Performance measurement has become widespread across many industries, including construction (Bassioni et al., 2004), since the extent to which a company achieves its financial and other objectives by spending less money and time as much as possible is crucial for success and survival. Measuring project performance enables companies to predict their projects'

potential success or failure (Galjanić et al., 2023). Overseeing material costs, equipment expenses, scheduling, process management, quality control, safety protocols, and operations during the construction phase, and measuring performance in various financial and other metrics enhance cost-effectiveness and progress toward company goals (Shin et al., 2024). However, Luu et al. (2008) mention that contractors, especially in developing countries, lack effective methods to evaluate their performance by pinpointing weaknesses and threats and suggest that they must periodically measure their performance to find out what should be improved (Luu et al., 2008). Therefore, in this study, we propose that Construction 4.0 and BMI are the drivers of firm performance in construction and measure firm performance in terms of financial and market success indicators.

2.3. Digital transformation and Construction 4.0

Strategic intentions, priorities, resources, competencies, capabilities, etc., accumulated, refined, and embedded within the organizational structure and culture, constitute the necessary driving forces to innovate and change the present business modelling to adapt, embrace and cope with the intense waves of transformation. In this sense, digital transformation is seen as an opportunity for better organizational performance since it creates entirely new business models (Mergel et al., 2019).

Some researchers have studied the relationships between digital technology usage and firm performance and the mediator role of organizational innovation. It can be assumed that some large companies in the developing countries' advanced sectors try to adapt themselves to the transformational megatrends by renovating their organizational structures, processes, techniques, models, etc. However, almost all industries and/or organizations are facing similar imperative pressures nowadays. Most of them, especially traditional organizations of developing countries, have not fully adopted new digital and physical technologies of construction yet; this forces researchers to examine different aspects of these transformation efforts and their performance impacts in developing countries, as suggested in the recent literature (Liu, 2020; Xia et al., 2024).

Construction 4.0 is a relatively new term which refers to adopting the concept of Industry 4.0 and its constituents by the construction industry (FIEC, 2015; García de Soto et al., 2022). For instance, a construction firm's beginning to utilize new digital technologies (in such domains as architecture, design, lean processes and systems, further automation of construction activities, project management, etc.) can be seen as adopting Construction 4.0 to combat design complexity, low productivity, skilled labour shortages in order to make buildings not only more efficient (in terms of waste, cost and time) but also safe and sustainable (Rastogi, 2017; Osunsanmi et al., 2018; Forcael et al., 2020; Hossain et al., 2020; Perrier, 2020; Begić and Galić, 2021). According to the European Construction Industry Federation, Construction 4.0 repesents the construction sector's adoption of Industry 4.0, characterized by the digitalization of this industry through advanced processes and technologies such as BIM (building information modelling), prefabrication, 3D printing, robotics, drones, equipment with sensors, interconnected machines, digital control systems, etc. These innovations aim to better perform repetitive and dangerous procedures, survey and control building sites, make construction faster but with fewer errors, etc. (FIEC, 2015). This radical transformation represents a major shift from the traditional organizational culture of construction companies having a limited innovation notion, and a major challenge to cope with the 4th industrial revolution of smart networking and full-scale automation-far beyond the earlier ones (mechanization of Industry 1.0, electrification and assembly lines of Industry 2.0, computerized automation of Industry 3.0) (Craveiro et al., 2019; Klinc and Turk, 2019). Awareness among the managers of the construction sector about digital transformation is limited, and accordingly, the transformation in their sector is slow (Osunsanmi et al., 2018; Adekunle et al., 2021). In addition, it is not easy to differentiate between technologies of Industry 3.0 (more related to computerized automation hardware) and technologies of Industry 4.0 (more related to digital networking systems) in the

Table 1
Digital and physical layers of construction 4.0

Construction 4.0: Emerging Technologies and their Functions	
1. Digital Layer (DL)	
AR/VR	*Augmented and Virtual Reality applications and augmentation of a real-world scene for all project phases to serve team members.*
Artificial Intelligence	*Classifying, predicting, image processing, mining, and problem-solving in such areas as cost and schedule overruns, safety concerns, etc.*
Big Data Analytics	*Trend analysis and business intelligence to assist teams to identify possible risks and problems at the site*
Blockchain	*Smart contracts to solve problems related to traditional contract forms, building trust and maintaining records.*
Building Information Modeling (BIM)	*Modeling and simulation for designing and managing information on a construction project during its life cycle.*
Cloud technologies	*Cloud-based digital tools to support Project Management*
Common Data Environment(CDE)	*Collect, manage, document, and disseminate project information, as well as graphical data, to serve team members.*
Cyber Security	*Securing the physical-digital-physical loop; detecting cyber risks, protecting critical data and recovering from cyber incidents.*
Laser Scanner	*Point cloud data collection; known as high-definition surveying*
Unmanned Aerial Systems	*Remotely-piloted Unmanned Aerial Systems for aerial image collection*
2. Physical Layer (PhL)	
Additive Manufacturing	*Print parts and products, and do autonomous production using BIM.*
Equipment with Sensors	*Assembly of parts and products in a location aware environment.*
Internet of Things (IoT)	*Connectivity of things, people and data to control the construction site.*
Offsite Construction	*Use manufacturing to produce parts and products.*
Robotics & Automation	*Transport assembly and production: build walls and blocks using 3D CAD models.*
Sensors & Wearable Sensors	*Collect information on location, temperature, humidity and movement to assess the safety and progress of the project.*

Source: (adapted from Sawhney et al., 2020; Osunsanmi et al., 2020)

perceptions of the traditional sectors' managers. Therefore, a general list of technologies to be adopted as Construction 4.0 technologies would be necessary. In this concern, we adapt the classifications developed and used by Sawhney et al. (2020) and Osunsanmi et al. (2020) to our study. Its layers are presented in Table 1.

There is a growing interest in construction management in digital technologies like virtual reality (VR) and augmented reality (AR) (Seyman Guray and Kismet, 2023). The digital layer of Construction 4.0 encompasses other technologies, such as big data analytics, BIM, artificial intelligence (AI), etc, that facilitate real-time data collection, collaborative planning, and predictive analytics to enhance project management and decision-making processes. Specifically, adopting AI in construction engineering and management can significantly improve automation, risk mitigation, efficiency, digitalization, and computer vision (Pan and Zhang, 2021). Additionally, the use of big data in the construction industry is rapidly expanding, with machine learning, data mining, and blockchain technologies showing great promise for enhancing safety, reducing energy consumption, and improving cost prediction (Lu and Zhang, 2022). Also, blockchain technology can strengthen construction business processes and information integration, offering potential benefits and challenges for public and private platforms (Yang et al., 2020).

Recent research has also focused on construction physical technologies. The physical layer of Construction 4.0 involves the adoption of advanced materials, robotics, automation, and 3D printing in construction processes. These advancements aim to enhance efficiency, reduce labour-intensive tasks, and optimize resource utilization on construction sites. Additive manufacturing can improve construction efficiency and reduce waste in off-site construction by fabricating complex shapes based on computer-aided design (CAD) models (Pasco and Aranas, 2022). Additionally, sensor-based technology significantly enhances construction safety management by enabling real-time, efficient, and accurate data collection and processing (Zhang et al., 2017).

3. Hypothesis development

In today's era of Industry 4.0, the amount of investment and usage of advanced technologies and their effects on innovation and performance become an interesting domain that is still mostly under-researched in the traditional sectors of developing countries. Therefore, in this study, we take into consideration the extend and type of digital and physical layers of Construction 4.0 and their relations to BMI and firm performance in the Turkish construction sector (as a traditional industry of a developing country). Accordingly, we develop the following hypotheses purporting that adopting the elements of Construction 4.0 would help construction firms renovate their business models and improve their organizational performance.

3.1. The relationship between Construction 4.0 and BMI

Vaska et al. (2021) infer that digital transformation positively impacts value creation, delivery, and capture, leading to the development of various new business models in almost every industry. However, there is a scarcity of empirical studies that employ a business model approach to examine organizational and managerial challenges within the building and construction context (Zhao et al., 2017; Liu et al., 2017). To our knowledge, no empirical studies directly focus on the relations between Construction 4.0, business model innovation, and firm performance. Still, some recent studies focus on some separate elements of Construction 4.0. For instance, adopting *Blockchain* technologies would help firms catalyze digital transformation, shape new business models and unify the industry through consortia, according to the studies of Nowiński and Kozma (2017) and Hackius and Petersen (2020). Using *AR/VR* in the construction industry can yield significant time and cost savings, resulting in enhanced profitability according to Ahmed (2018). Similarly, Safa and Hill (2019) emphasize the necessity of using *big data analytics* in construction management, considering its significant contributions to time, energy, and cost savings. Bello et al. (2020) find that *cloud computing* is an innovation delivery enabler for other emerging technologies (building information modelling, internet of things, AR/VR, big data analytics) in the construction industry. Again, Pessoa et al.'s (2021) study confirms the feasibility of employing *artificial intelligence* as an auxiliary mechanism for planning construction projects, particularly in the public sector. These recent studies imply that adopting and using the mentioned digital elements would positively impact BMI. Moreover, in this study, we put forth that they altogether (as depicted in Table 1) constitute the digital layer of Construction 4.0, and this construct affects BMI positively:

H1a. *the digital layer of Construction 4.0 is positively related to BMI.*

Empirical studies on adopting the physical layer of Construction 4.0 are limited to our knowledge. However, these scarce studies still imply that adopting the physical elements of Construction 4.0 would positively impact BMI as in the case of its digital elements. For instance, according to Sutrisna and Goulding (2019), *Offsite Construction* technology usage helps construction firms minimize design risks, and manage information flow and design processes in projects. Also, according to Martens et al. (2022), adopting *Additive Manufacturing* is positively related to BMI and productivity. Recent studies imply that the adoption and usage of these physical elements would produce positive impacts on BMI. Moreover, in this study, we purport that they altogether (as depicted in Table 1) constitute the physical layer of Construction 4.0 and this construct affects BMI positively:

H1b. *the physical layer of Construction 4.0 is positively related to BMI.*

3.2. The relationship between Construction 4.0 and firm performance

Few studies show the benefits and performance impacts of adopting Construction 4.0 (e.g., Alwan et al., 2017; Osunsanmi et al., 2020; Yang et al., 2022). According to Osunsanmi et al. (2020), adopting these new technologies increases competitiveness in the construction sector by enhancing performance in project design, management, operations, and decision-making. According to

Amankwah-Amoah et al. (2021), productivity often drops just after integrating new technologies, but then recovers. For instance, these technologies lower operational costs, improve construction site observation, prevent theft in construction sites, and provide safety management systems (Štefanič and Stankovski, 2018; Edirisinghe, 2019). In a longitudinal study conducted in Chinese construction firms, Yang et al. (2022) have recently confirmed that Construction 4.0 positively affects firm performance. However, Osunsanmi et al. (2020) claim that construction professionals in South Africa do not see smart construction technologies as very important and that the possibility of fully integrating Construction 4.0 into the construction industry seems low. Therefore, the separate individual effects of each of the two layers of Construction 4.0 on firms' performance need to be analyzed in another developing country context with the following hypotheses:

H2a. *the digital layer of Construction 4.0 is positively related to Firm Performance.*

H2b. *the physical layer of Construction 4.0 is positively related to Firm Performance.*

3.3. The relationship between BMI and firm performance

Past literature on innovation management, on the one hand, has already dealt with the performance impacts of different innovation types (product, process, marketing, etc.) on firm performance (e.g., Ulusoy et al., 2008; Shaukat et al., 2013; Park and Kwon, 2018). Beyond the separate innovation types, on the other hand, to uncover the big picture of innovativeness in the whole model of organizational activities, research on BMI has also studied its constituents and their performance impacts (e.g., Mitchell and Coles, 2004; Giesen et al., 2007; Massa and Tucci, 2014). In this concern, BMI refers to the reconfigurations, modifications and improvements done within the existing model of an established firm, which integrates a new logic to increase profitability or to capitalize on new business opportunities from new technology, new customer insights or new markets (Trapp et al., 2018; Wang and Zhou, 2021). This concept encompasses evolutionary and/or revolutionary modifications done in one or more elements within the four areas of innovation: value proposition, operational value, human capital, and financial value (Ramdani et al., 2019). As firms grow and institutionalize, they need to embed their dynamic capabilities and innovativeness in their procedures and routines, especially regarding BMI (Ogrenci et al., 2023). Likewise, improvements such as process optimizations, customer interface improvements, new value networks, smart products, and services, etc., might also improve firm performance (Ibarra, 2018). In this sense, past literature has already mentioned the positive effects of BMIs on the various aspect of firm performance (e.g., Giesen et al., 2007; Chesbrough, 2010; Zott et al., 2011). For instance, according to a recent survey conducted in European countries by Latifi et al. (2021), BMI improves organizational capabilities, efficiency, revenue, and overall firm performance. Therefore, we purport the following hypothesis:

H3. *BMI is positively related to Firm Performance.*

3.4. The mediator role of BMI in the relations between digital and physical layers of Construction 4.0 and firm performance

Beyond the performance-related consequences of BMI, Foss and Saebi(2017) have recently mentioned in their systematic literature review that there are still significant gaps in the search for the organizational drivers of BMI through the lenses of the dynamic capabilities view. Recent studies have begun to search for the mediating role of BMI in the relationship between organizational capabilities/capacities and firm performance in various sectors of developing and developed countries. For instance, an empirical study conducted in Chinese manufacturing firms found that BMI mediates the relationship between various dimensions of strategic flexibility capabilities and various aspects of firm performance (Xiao et al., 2023). However, Evans et al. (2017) emphasize the gaps in addressing the interaction between BMI and sustainability concerns. As for the Construction 4.0–business model–firm performance linkage, capabilities of incorporating into the business model some innovative elements related to digitalization have also become critical. For

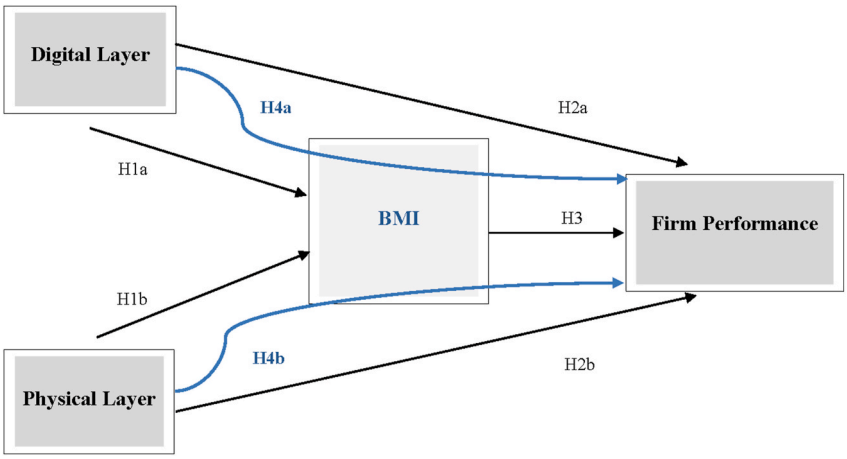


Fig. 1. Hypothetical model of relations.

instance, according to Vaska et al. (2021), digital transformation in business models enhances value creation, delivery, and capture in almost every industry. Considering the central role of BMI in organizational capabilities and firm performance, we propose in this study that BMI transfers the positive effects of Construction 4.0 to firm performance. In other words, the organizational capabilities of Construction 4.0 (both Digital and Physical) technologies contribute to BMIs that lead to the improvement of firm performance. Therefore, we develop the following hypotheses:

H4a. *BMI mediates the relation of digital layer of Construction 4.0 on firm performance*.

H4b. *BMI mediates the relation of physical layer of Construction 4.0 on firm performance*.

Fig. 1 depicts our proposed relations of the digital and physical layers of Construction 4.0 to BMI and firm performance, summarizing our hypothesis development process. On one hand, H1a, H2a, and H4a try to answer our first research question "How does the digital layer of Construction 4.0 relate to BMI and firm performance in the construction sector in a developing country context?" On the other hand, H2a, H2b, and H4b try to answer our second research question "How does the physical layer of Construction 4.0 relate to BMI and firm performance in the construction sector in a developing country context?" Two curved lines indicate the bridging roles of BMI to convey the positive effects of both digital and physical layers of Construction 4.0 on firm performance.

4. Methods

4.1. Measures

In this questionnaire study, we measured all variables using the 5-point Likert scale method to reduce the cognitive load and anxiety caused by too many options for the respondents, establish balance with a neutral value (3) in the middle, and facilitate comprehension and clear answers for readers.

Construction 4.0: This scale has 18 items. We developed it from two studies (Sawhney et al., 2020; Osunsanmi et al., 2020). It includes two dimensions: the digital layer (DL) and the physical layer (PL) of Construction 4.0. The scale of the first dimension (digital layer) has 10 items beginning with the starting question: 'The most frequent digital uses of Construction 4.0 technologies are listed below; how often do you use these technologies.' Cronbach's alpha coefficient of this scale is $\alpha = 0.84$. The scale of the second dimension (physical layer) has 8 items beginning with: 'the most frequent on-site use of Construction 4.0 technologies is listed below; how often do you use these technologies'. Cronbach's alpha coefficient of this scale is $\alpha = 0.74$. The Construction 4.0 scale was assessed using a 5-point Likert scale, ranging from 1 (Never) to 5 (Always).

BMI: This scale has 22 items. They are adapted from the scales of Clauss (2017), and Ogrenci and Alpkan (2023), beginning with the starting question: 'Choose your level of agreement to answer the following questions based on your observation and knowledge regarding your last project'. Cronbach's alpha coefficient of this scale is $\alpha = 0.97$. The BMI scale was assessed using a 5-point Likert scale, with responses ranging from 1 (Strongly disagree) to 5 (Strongly agree).

Firm performance: This scale has 10 items we adopted from Santos and Brito (2012), beginning with the starting question: 'Evaluate the following questions based on your observations and knowledge. How has your company situation changed in the following items compared to competitors in the last five years. Cronbach's alpha coefficient of the scale is $\alpha = 0.94$. The firm performance scale was measured on a 5-point Likert scale, ranging from 1 (Very poor) to 5 (Very good).

4.2. Data collection procedure and test of non-response bias

The survey was conducted via a questionnaire study on the managers of Turkish construction companies. The available communication links of these companies are obtained from various sources, including Chambers of Civil Engineers, Chambers of Architects, etc. Hence, a purposive sample, such as non-probability convenience sampling, was adopted in this study. An online questionnaire link was sent via e-mail to 835 construction firms, then a second wave of e-mail postings by the Union of Chambers of Turkish Engineers and Architects, reminder phone calls and site visits were also made; and finally, 152 valid surveys were obtained within our study's time limits. Most of those who did not respond declared they were busy or did not want to share information. As for the responding managers, half of them had 10 years and above experience in the sector, 25% had experience of 3–10 years, and the remaining 25% had experience below 3 years. Because respondents completed the survey at different times or some of them did not complete it, and because the number of responses was less than half of the total number of surveys that were initially distributed, we conducted a nonresponse bias analysis to detect any systematic difference between early (18%) and late responses (82%) (Armstrong and Overton, 1977). The results showed no statistically significant difference between the variables' early and late responses ($p > 0.05$).

5. Findings

The collected data were analyzed using R statistical language (R Core Team, 2022). Descriptive statistics, validity and reliability test, correlation analysis, explanatory factor analysis, and Hayes's (2022) PROCESS (Model 4) analysis were used for data analysis and hypotheses tests.

Before the main analyses, some preliminary analyses were conducted to test whether there were outliers. Accordingly, skewness and kurtosis values of all items and constructs were examined. As Kline (2023) suggested, the skewness and kurtosis values should not exceed absolute values 3 and 10, respectively. Because the skewness values were in the ranges of .240–1.261 and the kurtosis values were in the ranges of .040–3.207, the data distribution was not affected by outliers. Based on the mentioned indicators and central limit

theorem assumptions (Barany and Vu, 2007), it was provided that the data were normally distributed.

5.1. Construct validity and test of common method bias

Explanatory factor analysis was conducted to test construct validity. Accordingly, as seen in Appendix A, in the first factor analysis that evaluates the construct validity of Construction 4.0, two factors were extracted based on eigenvalue 1 and over. While the first factor represented the digital layer of the construct and explained 38.40% of the total variance, the second factor represented the physical layer of the construct and explained 10.91% of the total variance. The amount of the total variance extracted by two factors of Construction 4.0 was 49.31% (Appendix A). Appendix B shows that the second factor analysis that evaluates the construct validity of the independent and mediator variables extracted two actors based on eigenvalue 1 and over. While the first factor represented the BMI and explained 49.77% of the total variance, the second factor represented firm performance and explained 20.36%. The amount of the total variance extracted by these two factors was 70.13%. The results of the construct validity assessment showed that the constructs were valid.

Harman's single factor method was followed to test common method bias (Podsakoff et al., 2003). Accordingly, one factor that represents all items explained 30.86 %, below the threshold value 50%, indicating that the common method bias does not exist in this study.

5.2. Internal reliability, descriptive statistics, and correlations

We calculated Cronbach's alpha coefficients to assess the internal reliability of our constructs. Cronbach's alphas were as follows: digital layer's $\alpha = 0.84$, physical layer's $\alpha = 0.74$, BMI's $\alpha = 0.97$, Performance's $\alpha = 0.94$—all being above the suggested threshold value ($\alpha = 0.70$) to be assumed reliable (Cronbach, 1951).

Table 2 depicts the descriptive statistics (M = means and SD = standard deviations) of the Construction 4.0 components and their correlations to BMI and firm performance. The extent of digital technology usage in the Turkish Construction Sector seems to be very low (1.80 for digital layer and 1.73 for physical layer on a scale 1–5). Only the average usage of AI and Blockchain technologies of the digital layer and that of Offsite Construction and Sensors technologies of the physical layer seem still low, but relatively higher when compared to the other components. As for the least used technologies, the mean values of Unnamed Aerial Systems among the constituents of the digital layer and Actuators among the constituents of the physical layer are the lowest.

Table 2 also presents one-to-one correlations of the components of the digital and physical layers of Construction 4.0 to BMI and firm performance. This reveals a positive and significant correlation between the digital components of Construction 4.0 and BMI, except for cyber security and AI technologies. When all these components are combined under the general title of the digital layer of Construction 4.0, this construct is again positively and significantly correlated to both BMI ($r = .33$, $p > 0.01$) and firm performance ($r = .18$, $p > 0.05$). However, one-to-one correlations of most of the digital layer components (except Big Data Analytics and AI) to firm performance are insignificant. As for the physical layer of Construction 4.0, there is a positive and significant correlation between its components and BMI (except for Offsite Construction and Sensors). Similarly, there is a positive and significant correlation between physical layer components and firm performance (except for the technologies of Actuators and Additive Manufacturing). When all these physical components are combined under the general title of the physical layer of Construction 4.0, this construct is again positively and significantly correlated to both BMI ($r = .30$, $p > 0.01$) and firm performance ($r = .19$, $p > 0.05$).

Table 2
Means, standard deviations, and correlations among dimensions of Construction 4.0, BMI and firm performance.

Components of the Digital Layer of Construction 4.0	*M*	SD	BMI	Firm Perf.
Digital Layer (all together)	**1.80**	**.74**	**.33****	**.18***
1. Big Data Analytics	1.66	1.05	.38**	.18*
2. Unnamed Aerial Systems	1.37	.89	.23**	.06
3. Cyber Security	1.90	1.21	.08	.05
4. Cloud Based Project Management	1.42	.83	.23**	.08
5. AR/VR	1.48	.87	.29**	.15
6. AI	2.53	1.36	.14	.23**
7. Blockchain	2.15	1.17	.18**	.10
8. CDE	1.89	1.12	.32**	.15
Components of the Physical Layer of Construction 4.0	***M***	**SD**	**BMI**	**Firm Perf.**
Physical Layer (all together)	**1.73**	**.70**	**.30****	**.19***
1. Actuators	1.22	.57	.26**	.07
2. Equipment with sensors	1.57	1.00	.21*	.21*
3. Additive Manufacturing	1.50	.97	.28**	.10
4. Offsite Construction	2.28	1.32	.16	.16*
5. Sensors	2.20	1.25	.16	.16*
6. IoT	1.63	1.04	.24**	.28**

Note. M and SD are used to represent mean and standard deviation, respectively.
* indicates $p < 0.05$. ** indicates $p < 0.01$.

5.3. Hypothesis testing

R statistical language was used to test research hypotheses. While the direct hypotheses were tested using simple linear regression analysis, mediator hypotheses were tested using PROCESS codes with Model 4 (for simple mediation analysis) developed by Hayes (2022). Compared with the conventional methods (e.g., Baron and Kenny, 1986), the main advantages of PROCESS analysis are that it tests both sample adequacy for the mediation analysis using the bootstrap method and the significance of the indirect effect by using the upper and lower confidence interval. Accordingly, if the indirect effect falls into the confidence interval including zero (from minus to positive or starting from zero to positively infinite), it can be said that the indirect is non-significant. However, when the confidence interval does not include zero, it means the significance of the indirect effect.

As shown in Table 3, Construction 4.0's digital layer affects BMI positively and significantly ($\beta = .44$, $p = 0.000$) and firm performance ($\beta = .22$, $p = 0.023$), supporting H1a and H2a. The results also show that BMI positively and significantly affects firm performance ($\beta = .22$, $p = 0.004$). Therefore, H3 is also supported. Moreover, the effect of the digital layer on firm performance, which is positive and significant in the first step, becomes non-significant when BMI is included as a mediator (indirect effect = .10; BCa CI [.026, .191]). In other words, BMI fully mediates the positive link between digital layer of Construction 4.0 and firm performance. Therefore, H4a is supported.

As shown in Table 4, Construction 4.0's physical layer sub-dimension positively affects BMI ($\beta = .43$, $p = 0.000$) and firm performance ($\beta = .24$, $p = 0.023$), supporting H1b and H2b. Moreover, the effect of the physical layer on firm performance, which is positive and significant in the first step, becomes non-significant when BMI is included as a mediator (indirect effect = .07; BCa CI [.020, .147]). In other words, BMI fully mediates the positive link between physical layer of Construction 4.0 and firm performance. Therefore, H4b is supported. Therefore, our hypothesis-testing process supported all proposed hypotheses, as depicted in Table 5.

Fig. 2 depicts our proposed and supported relations of the digital and physical layers of Construction 4.0 to BMI and firm performance as a result of our hypothesis testing process. The Box of "Digital Layer" represents our independent variable constructed as the aggregation of the digital components of Construction 4.0, namely Big Data Analytics, Unnamed Aerial Systems, Cyber Security, Cloud Based Project Management, AR/VR, AI, Blockchain, CDE. The Box of "Physical Layer" represents our independent variable constructed as the aggregation of the physical components, namely Actuators, Equipment with sensors, Additive Manufacturing, Offsite Construction, Sensors, and IoT. The arrows imply supported relations, beta coefficients indicate their effect sizes, and dotted lines show the relations that the mediation of BMI overshadows.

6. Discussions and conclusion

Our empirical study on the extent of construction technology usage in the Turkish construction sector and their relations to BMI and firm performance reveals that, on the one hand, the adoption of digital and physical technology in the construction sector, as in other developing countries, is still in its early stages. There are many challenges in integrating these new technologies. However, on the other hand, the adoption of both digital and physical layers is positively and significantly related to BMI and firm performance in our study. More specifically, we find that BMI plays a full mediator role in the relations of both digital and physical layers of Construction 4.0 on firm performance.

As for the theoretical implications, this study contributes to the fields of dynamic capabilities and BMI by testing and confirming the central role of BMI as a missing link between digital capabilities and firm performance in a traditional industry of a developing country. Similarly, in a recent study on the construction sector of another developing country, Pakistan, Idrees et al. (2023) find that organizational focus on innovation mediates the effects of knowledge management capabilities on organizational performance. Indeed, some recent studies have already mentioned the central role of BMI between organizational capabilities and firm performance, especially in the era of Industry 4.0 (e.g., Vaska et al., 2021; Xiao et al., 2023). However, our findings do not only confirm the role of the general concept of innovation, specifically BMI, as a mediator but also emphasize BMI as a critical bridge that links the adoption of necessary digital and physical technologies of Construction 4.0 to firm performance only if the business model as a whole (beyond separate innovation efforts) is renowned. Otherwise, every technology adoption does not automatically end up with higher performance. This implies that the digital transformation of the way of doing business within the whole organizational mechanism can fulfill a bridging function between technology adoption and firm performance.

Table 3
Test results for H1a, H4a.

Relationship	β	S.E.	C.R.	p
DL → BMI (Path a)	0.44	0.10	4.28	0.000***
BMI → Perf. (Path b)	0.22	0.07	2.96	0.004**
DL → Perf. (Direct effect: path c')	0.13	0.11	1.25	0.211 n.s.
DL → Perf. (Total effect: path c)	0.22	0.10	2.31	0.023*
Bootstrap analysis of the mediating effect				
	Indirect effect	%95 LL	%95UL	
DL → BMI → Perf.	0.10	0.026	0.191	

Note: Number of bootstraps for percentile bootstrap confidence intervals: 5000.
* indicates $p < 0.05$, ** represents $p < 0.01$, and *** is $p < 0.001$. n.s. indicates no significance.

Table 4
Test results for H1b, H4b.

Relationship	β	S.E.	C.R.	p
PL → BMI (Path a)	0.43	0.11	3.85	0.000***
BMI → Perf. (Path b)	0.22	0.07	3.01	0.003**
PL → Perf. (Direct effect: path c')	0.14	0.11	1.36	0.177 n.s.
PL → Perf. (Total effect: path c)	0.24	0.10	2.31	0.023*
Bootstrap analysis of the mediating effect	Indirect effect	%95 LL	%95UL	
PL→ BMI → Perf.	0.10	0.020	0.147	

Note: Number of bootstraps for percentile bootstrap confidence intervals: 5000.
* indicates $p < 0.05$, ** represents $p < 0.01$, and *** is $p < 0.001$. n.s. indicates no significance.

Table 5
Summary of Relations stated in the Hypotheses and their test results.

No.	Statement of Relations	Supported
H1a	The digital layer of Construction 4.0 is positively related to BMI.	Yes
H1b	The physical layer of Construction 4.0 is positively related to BMI	Yes
H2a	The digital layer of Construction 4.0 is positively related to firm performance.	Yes
H2b	The physical layer of Construction 4.0 is positively related to firm performance.	Yes
H3	BMI is positively related to firm performance.	Yes
H4a	BMI mediates the relation of digital layer of Construction 4.0 on firm performance.	Yes
H4b	BMI mediates the relation of physical layer of Construction 4.0 on firm performance.	Yes

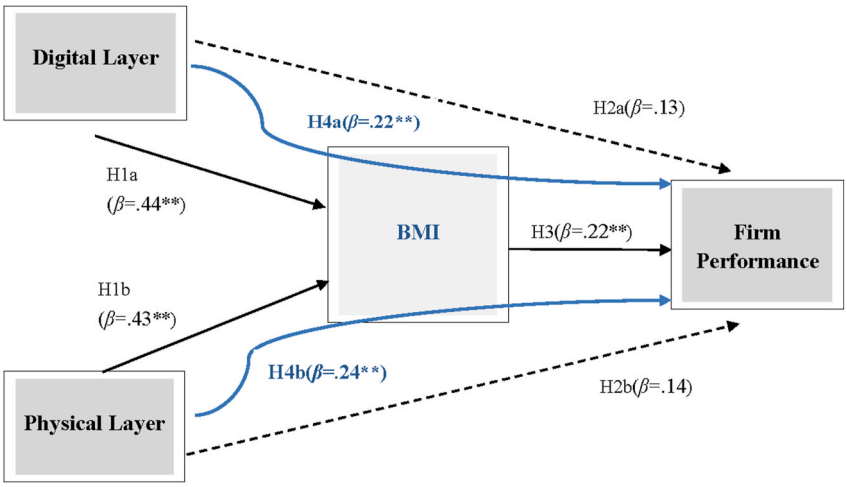


Fig. 2. Resulting model of relations.

As our findings indicate that the extend of use of Construction 4.0 technologies both digital and physical is low, we can highlight construction firms as the primary beneficiaries of adopting Construction 4.0 integrated with BMI. These technologies offer distinct benefits throughout the project life cycle at various phases. During the planning phase, firms benefit from precise design visualization and resource allocation facilitated by Building Information Modelling. In the execution phase, robotics and automation enhance operational precision and productivity. Real-time data analytics enable proactive adjustments in the monitoring phase, while digital twins streamline maintenance and management in the closing phase, promoting sustainability and innovation post-project completion. The circumstances under which these benefits are most pronounced include early adoption strategies, allowing firms to anticipate industry shifts and stay ahead of competitive pressures. Strategic BMI practices are essential, ensuring that technological investments translate into sustainable competitive advantages by aligning innovation efforts with strategic priorities to create and capture innovative business value effectively. These insights underscore the critical importance for construction managers, particularly in developing countries like Turkiye, to adopt and integrate digital and physical technologies through robust BMI practices across all phases of construction projects. This approach enhances project efficiency and quality and strategically positions firms to thrive in the evolving landscape of Industry 4.0. Again, triggering experts' innovative solutions in terms of new designs, new processes, or new marketing campaigns to deal with unmet customer needs and expectations about smart buildings before and better than competitors is not enough. Rather, a comprehensive renovation of BMI based on strategically congruent priorities to create and capture innovative

business value is a must to tie dynamic capabilities with higher performance. Otherwise, separate innovative efforts of creative individual managers would be spent in vain on the eve of Construction 4.0.

This survey study is not free from various limitations, of course. Firstly, the conceptualization, diffusion, and utilization of Construction 4.0 digital and physical technologies are still relatively new for most construction sites in our context. This might limit performance in the future. Longitudinal studies that confirm causal relations and qualitative studies that tie specific transformational factors to different aspects of value creation and capture would enlarge our understanding of organizational learning and development. Secondly, responding managers who participated in our survey—as a single respondent from every construction company, tried to envisage and evaluate various constituents of BMI and other variables. Although this might raise concerns about common method bias, the test results for Harman's single factor method relieved these concerns, as mentioned in the methodology section. Thirdly, since our survey is conducted only on Turkish construction companies, our ability to generalize findings for all the developing countries is somewhat limited. Accordingly, we suggest that similar empirical studies to test the effects of digital transformation might be conducted again in traditional sectors but in other developing countries in the future.

To conclude, our study reveals that BMI plays a central role in turning dynamic capabilities into superior performance, especially concerning the digital and physical layers of Construction 4.0. Firms that can develop capabilities to adopt and exploit advanced technologies in traditional sectors can renovate their business models successfully and sustain their competitiveness in the era of Industry 4.0.

Ethics statement

The questionnaire received approval for use in the research from Istanbul Technical University Ethics Committee for Human Studies in Social Sciences and Humanities, as per the decision dated May 16, 2022 (Number 257).

Data availability statement

Data analyzed during the study are available from the corresponding author by request.

Declaration of competing interest

No conflict of interest was declared by the authors.

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Appendix A

Exploratory Factor Analysis for Construction 4.0

Items	Digital	Physical
DL1. Big Data Analytics (Trend analysis and business intelligence.)	.785	
DL2. Unmanned Aerial Systems (Aerial image collection)	.699	
DL3. Cyber Security (Securing the physical-digital-physical loop.)	.685	
DL4. Cloud-based Project Management (Digital tools to support delivery and business processes)	.667	
DL5. AR/VR (Virtual application for all phases and for all team members.)	.652	
DL6. Artificial Intelligence (Classifying, predicting, image processing, mining and problem-solving.)	.620	
DL7. Blockchain (Smart contracts, building trust and maintaining records.)	.619	
DL8. CDE (Collect, manage and disseminate documentation, the graphical data for the whole project team.)	.616	
PL1. Actuators (Convert digital interactions into physical action.)		.741
PL2. Equipment with Sensors (Assembly of parts and products in a location aware environment.)		.711
PL3. Additive Manufacturing (Print parts and products using the BIM model)		.647
PL4. Offsite Construction (Use manufacturing to produce parts and products.)		.627
PL5. Sensors (Collect location, temperature, humidity and movement information)		.547
PL6. IoT (Connectivity of things, people and data.)		.521
Cronbach's Alpha	$\alpha = 0.84$	$\alpha = 0.74$
Eigenvalues	4.050	2.853
% of variance explained	%38.40	%10.91
% of total variance explained	%49.31	

KMO = .845, Barlett's Test of Sphericity = 778.779 $p < 0.001$ Rotation converged in 3 iterations. Note: DL = Digital Layer, PL= Physical Layer.

Appendix B

Exploratory Factor Analysis for BMI and Firms Performance		
Items	BMI	Perf.
BMI1.We regularly evaluated new technological opportunities to expand our product and service portfolio.	.860	
BMI2. We used innovative/modern methods to increase client retention.	.856	
BMI3. Our products or services have been more innovative than our competitors.	.843	
BMI4. We regularly considered new and underserved market segments.	.836	
BMI5. Recently, we have taken many steps to strengthen client relationships	.834	
BMI6. We regularly reviewed emerging and unmet client needs.	.828	
BMI7. We regularly reviewed and tried to improve existing processes.	.828	
BMI8. Our products or services have solved client needs that cannot be solved by competitors.	.808	
BMI9. We tried to keep our company's technological resources up to date.	.805	
BMI10. We regularly evaluated the opportunities emerging in new or growing markets.	.805	
BMI11. We have continually reviewed our pricing strategy and evaluated alternatives.	.805	
BMI12. We were able to significantly improve our workflow processes.	.802	
BMI13. We used innovative procedures and processes during the production of our products.	.799	
BMI14. We kept our technological equipment more up-to-date than our competitors.	.798	
BMI15. Thanks to the various training we provide to our employees, we have gained new knowledge, skills and competencies	.788	
BMI16. New collaborations regularly helped us further develop our business model.	.780	
BMI17. Our employees have much more up-to-date information and new skills than our competitors' employees.	.777	
BMI18. We have continually explored what competencies we need to adapt to changing market requirements.	.744	
Perf1. Return on assets (profit/total assets)		.922
Perf2. Company's overall profitability		.914
Perf3. Cash flow (excluding investments)		.897
Perf4. Total profit		.856
Perf5. Market share		.842
Perf6. Number of new projects		.804
Cronbach's Alpha	$\alpha = 0.97$	$\alpha = 0.94$
Eigenvalues	12.666	4.165
% of variance Explained	%49.768	%20.362
% of total Variance Explained	%70.130	

KMO = .91, Barlett's Test of Sphericity = 4345.941$p < 0.001$ Rotation converged in 5 iterations. Note: BMI= Business Model Innovation, Perf. = Performance.

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