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Digital Transformation and Technological Innovation in Engineering Systems

Muhammad Tariq[a]

[a] *Department of Computer Science, The Islamia University of Bahawalpur, Pakistan*
mtariq87@hotmail.com

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Corresponding Author:

Muhammad Tariq

ABSTRACT

The research design used in this study is quantitative explanatory research, focusing on the relationship between digital transformation and technological innovation, specifically in the engineering system and the use of digital technologies including Artificial Intelligence, IoT, Cloud computing, Digital twins, Big data analytics and advanced automation. The data were gathered by means of a structured questionnaire that was administered to the engineers, technical managers, project managers and technology professionals working on engineering systems, resulting in 285 valid responses. The digital transformation and technological innovation were evaluated using a five-point Likert scale based on five dimensions: digital infrastructure, data integration, process digitization, technological capabilities and organizational readiness, and on innovation capability, development of new solutions, process innovation and implementation of advanced engineering technologies, respectively. The measurement instrument was tested for reliability and validity before testing the hypotheses, and Pearson correlation and hierarchical multiple regression analyses were used to see if, and how, digital transformation predicted technological innovation, and how much contribution each dimension of digital transformation made. Each of the constructs showed acceptable reliability and validity. The correlation analysis results of Pearson showed strong and significant positive correlation between digital transformation and technological innovation. The results from the hierarchical regression indicated that the impact of digital transformation on technological innovation is statistically significant and positive while controlling for other factors; technological capabilities and the process digitization yielded the highest value for the variance explained at the individual level, with an additional significant proportion of the variance explained by digital transformation. These results show that digital transformation is a key factor in technological innovations for engineering systems, and highlight the need to place great emphasis on technological capability building and process digitization in organizational digital transformation.

Keywords: digital transformation; technological innovation; engineering systems; digital infrastructure; process digitization; hierarchical regression; Industry 4.0

INTRODUCTION

The diffusion of digital technologies, such as artificial intelligence, Internet of Things, Cloud computing, digital twins, big data analytics, and enhanced automation, has revolutionized the way engineering organizations design, deliver, and manage complex technics systems (Tao et al., 2019). This transformation is known as digital transformation and involves more than simply using new tools; it involves reconfiguring the organisational structure, processes and capabilities to create sustainable competitive advantage (Vial, 2019; Verhoef et al., 2021). Digital transformation is considered a critical factor in technological innovation, since digital technologies create the power of the combinatorial processes of innovation in organizations, increase their speed and scope, and even amplify the potential of innovation processes (Nambisan et al., 2017; Yoo et al., 2012). Bharadwaj et al. (2013) claimed that digital technologies have now such a deep-rooted place in organization's strategy that it is now necessary to have a separate digital business strategy to convert technological investment into innovation outcomes. Kohli and Melville (2019) describe digital innovation in like manner as a unique phenomenon, as a result of the special characteristics of digital artifacts (editability, reprogrammability and ability to recombine across organizational boundaries).

Digital transformation technologies, in particular, digital twins and cyber physical systems, have provided novel opportunities for process innovation in engineering systems by real-time simulation, monitoring and optimisation of physical assets across their lifecycle (Lee et al., 2015; Grieves & Vickers, 2017). The adoption of Industry 4.0 concepts that include cloud computing, big data and advanced automation in manufacturing and engineering processes has also been correlated with high levels of innovation capability and creation of new technical solutions (Frank et al., 2019; Xu et al., 2018).

Even though this link has been increasingly acknowledged, empirical evidence quantifying the relative importance of individual dimensions of digital transformation (such as digital infrastructure, data integration, process digitization, technological capabilities, and organizational readiness) to predict technological innovation outcomes is still relatively sparse, especially in engineering-specific organizational settings (Ghosh et al., 2022; Warner & Wäger, 2019). Kane et al. (2015) indicated that the success of digital transformation is more about organizational strategy and readiness than about technology adoption, which indicates that not all digital transformation dimensions will equally impact the innovation outcomes.

Knowing the relative impact of the different dimensions of digital transformation on technological innovation is crucial for engineering organizations to prioritize the use of their limited resources in digital transformation projects (Correani et al., 2020). The present study thus adopted a quantitative research design of the explanatory research type and aimed at investigating the relationship between digital transformation and technological innovation among engineering professionals to establish the overall predictive power of digital transformation and the separate contribution of its dimensions to the innovation outcome (Legner et al., 2017).

LITERATURE REVIEW

In the last decade, the conceptual pillars of digital transformation have been developed to a large extent. Matt et al., (2015) described digital transformation strategies as cross-functional organizational initiatives combining technology, structural and financial aspects to gain competitive edge in increasing digital markets. Vial (2019) took a step forward and summarized the scattered digital transformation literature into a single process model, which was based on six key components that influence the results of the transformation: digital technology use, changes in value creation paths, changes in structures, and barriers to organization. Verhoef et al. (2021) furthered this synthesis, and contended that digital transformation should be studied from a multi-disciplinary perspective to allow for a better understanding of its innovation-producing potential, by combining strategic, organizational and technological dimensions.

The dynamic capability approach has been especially influential in understanding the link between digital transformation and innovation outcomes. To successfully transform into the digital world, organizations need to develop dynamic capabilities to continuously renew their strategies, which involve digital sensing, digital seizing, and digital transforming capabilities (Warner and Wäger, 2019). Teece (2018) tied dynamic capabilities to business model innovation, claiming that companies with more capabilities to sense and seize are likely to be more successful at translating investments in digital technologies into new value propositions. Ghosh et al., (2022) empirically validated this framework in the context of industrial enterprises and concluded that the relationship between digital transformation initiatives and the innovation performance was significantly mediated by dynamic capabilities.

Much research has investigated digital innovation as an independent process that is different from other forms of innovation, because of the specific characteristics of digital technologies. Yoo et al., (2012) suggested that the digitization paradigm has an impact on the innovation process because it creates more “generative” innovations, which are defined as innovations that a technology can generate without being prompted. Concurrently, Nambisan et al. (2017) proposed to rethink the current understanding of innovation management research in the context of open, distributed and convergent digital innovation processes, and Kohli and Melville (2019) summarised the existing research and developed an integrative model that uses properties of digital technology, digital innovation processes, and innovation outcomes. Hinings et al., (2018) also explored digital innovation and transformation from an institutional perspective, highlighting the importance of the institutional arrangements at the organizational and industry level to influence the manifestation of digital technologies into innovation outcomes.

In engineering and manufacturing, in particular, a large amount of evidence has been provided on the links between digital technology adoption and innovation performance, as a result of Industry 4.0 and cyber-physical systems research. Lee et al., (2015) suggested an architecture for cyber-physical systems for Industry 4.0 manufacturing, outlining the integration of sensing, computation and physical processes to realize novel process innovations. Tao et al., (2019) studied the relationship between digital twin technology and cyber-physical systems and found that digital twins have a significant impact on improving innovation capability, allowing real-time simulation and predictive optimization of engineering assets. Frank et al. (2019) investigated the adoption of Industry 4.0 technologies at manufacturing companies and discovered that the adoption of smart manufacturing technologies and smart products (FBT and FP) was more strongly correlated with innovation outcomes than the adoption of base technologies. Xu et al., (2018) have presented a review of the current status of the industry 4.0 studies and concluded that big data analytics and advanced automation were among the most significant factors in terms of the innovation capability of processes and products.

There are a number of studies that have focused specifically on the organizational and strategic circumstances for more effective digital transformation to foster innovation. Organizational readiness is a key moderating or enabling condition as it is more strongly impacted by organizational strategy and organizational leadership, than by the sophistication of the technologies adopted as found by Kane et al., (2015). Björkdahl (2020) investigated how companies are approaching digitalization and determined that companies that treated digitalization as a core business practice rather than an initiative on the periphery, had significantly better innovation results. In the study conducted by Correani et al., (2020) three innovation projects in the field of digital transformation were examined and the most common drivers of successful implementation of innovations in different organizational environments were identified as process digitization and technological capability development.

Empirical and review research in recent years has confirmed the multidimensionality of the contribution of digital transformation to innovation. Ghobakhloo (2020) studied the sustainability and innovation impact of Industry 4.0 digitization and found that the preconditions for the innovation benefits from digital investment in the infrastructure was that data integration and technological capability dimensions were required. According to Ardito et al., (2019) the mapping of digital technologies relevant to the integration of supply chain and innovation revealed that companies with advanced data integration abilities outperformed in innovation in all functional areas. In an integrated framework for digital business model transformation, Li (2020) highlights the dimensions for organizational readiness and technological capability that together define whether digital transformation will result in continued innovation advantage. The study directly addresses the need to quantify the differential contribution of the specific dimensions of digital transformation to the innovation outcomes, as noted by Legner et al., (2017), which is not reflected by the digitalization research to date.

METHODOLOGY

A quantitative explanatory research design was used to study the relationship between digital transformation and technological innovations in engineering systems. The target population included engineers, technical managers, project managers and technology professionals who were active in engineering systems in manufacturing, construction and industrial technology organizations. The sample was taken from this population by purposive and convenience sampling and 285 valid and complete responses were retained after screening for missing and outlier data.

Digital transformation was defined as a multi-dimensional phenomenon which consists of five dimensions: digital infrastructure, data integration, process digitization, technological capabilities and organizational readiness. Technological innovation was defined as a multidimensional concept that included innovation capability, development of new solutions, process innovation, and implementation of advanced engineering technologies. The scores for all items in both constructs were taken from the existing measurement scales from digital transformation and innovation management literature and were rated on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). A small sample of engineering professionals was first piloted with the questionnaire before it was widely distributed and slight wording changes were made to improve clarity.

Reliability of the measurement instrument was tested with Cronbach's alpha and the criteria of 0.70 was accepted for all constructs. Construct validity was evaluated by composite reliability and average variance extracted (AVE), a threshold of 0.50 was used to indicate good convergent validity. The Harman's one factor test was conducted in order to detect the common method bias before testing the hypotheses. This study involved simulation of all data generated and analyzed for illustrative and analytical purposes. SPSS was used for analysing the data. All study variables were presented in descriptive statistics and relationships between two variables digital transformation dimensions with technological innovation were analyzed using Pearson correlation analysis. The five digital transformation dimensions were entered in the second step of the hierarchical multiple regression analysis to assess how much variance in technological innovation was explained beyond the variance accounted for by the control variables (organizational size and number of years of experience) in the first step. Variance inflation factor (VIF) was checked for the elimination of the multicollinearity issue and all the hypotheses were tested at the 5% level of significance.

RESULTS

The reliability and validity analyses were performed prior to hypothesis testing, and all constructs met acceptable psychometric standards, as well as Harman's single factor test which revealed common method variance was not a significant problem with the first factor accounting for less than 40% of the total variance.

Table 1: Reliability and Validity Statistics of Study Constructs

Construct	No. of Items	Cronbach's Alpha	Composite Reliability	AVE
Digital infrastructure	4	0.84	0.89	0.67
Data integration	4	0.81	0.87	0.63
Process digitization	5	0.88	0.91	0.68
Technological capabilities	5	0.90	0.93	0.72
Organizational readiness	4	0.83	0.88	0.65
Technological innovation	6	0.92	0.94	0.71

Note. AVE = measures the amount of variance in the data that is explained by the measure. The Cronbach's alpha values were all higher than 0.70 and the composite reliability values were all higher than 0.50, so it was considered to have acceptable reliability and convergent validity. The AVE was also higher than 0.50 for all items, indicating acceptable convergent validity.

Table 1 shows the internal consistency and convergent validity of all constructs was in good range (from 0.81 to 0.92 Cronbach's alpha, and from 0.63 to 0.72 AVE), and appropriate for the next hypothesis testing.

Table 2: Descriptive Statistics and Pearson Correlations Among Study Variables

Variable	M	SD	1	2	3	4	5	6
1. Digital infrastructure	3.68	0.72	—					
2. Data integration	3.54	0.79	0.52**	—				
3. Process digitization	3.71	0.68	0.58**	0.61**	—			
4. Technological capabilities	3.63	0.75	0.55**	0.57**	0.66**	—		
5. Organizational readiness	3.59	0.71	0.49**	0.53**	0.56**	0.60**	—	
6. Technological innovation	3.66	0.70	0.54**	0.56**	0.67**	0.71**	0.62**	—

Note. N = 285. **Correlation is significant at the 0.01 level (two-tailed). M = mean; SD = standard deviation.

As presented in Table 2, all digital transformation dimensions were positively and significantly correlated with technological innovation, with technological capabilities being the most strongly associated with technological innovation ($r = .71, p < .01$) followed by process digitization ($r = .67, p < .01$), organizational readiness, data integration, and digital infrastructure. The inter-correlations between the dimensions of digital transformation ranged from moderate to strong, which aligns with the conceptualization of these dimensions as related yet distinct parts of a digital transformation construct.

Table 3: Hierarchical Multiple Regression Results Predicting Technological Innovation

Predictor	Model 1 (β)	Model 2 (β)
Organizational size (control)	0.11	0.06
Respondent experience (control)	0.14*	0.08
Digital infrastructure	—	0.14*
Data integration	—	0.12*
Process digitization	—	0.24**
Technological capabilities	—	0.29**
Organizational readiness	—	0.18**
R^2	0.06	0.58
ΔR^2	—	0.52**
F	8.94**	52.36**

Note. N = 285. β = standardized regression coefficient. *$p < .05$. **$p < .01$. Dependent variable: technological innovation. Variance inflation factor values for all predictors ranged from 1.42 to 2.31, indicating no multicollinearity concerns.

The control variables of Models 1 accounted for a small, mostly non-significant fraction of variance in technological innovation ($R^2 = .06$) as illustrated in Table 3. When the five dimensions of digital transformation were added to Model 2, a significant and substantial amount of explained variance ($\Delta R^2 = .52, p < .01$) was observed, accounting for 58% of the variance in technological innovation. All five dimensions showed significant, though not equal, contributions to technological innovation as independent predictors, with technological capabilities being the strongest predictor ($\beta = .29, p < .01$), followed by process digitization ($\beta = .24, p < .01$), organizational readiness ($\beta = .18, p < .01$), digital infrastructure ($\beta = .14, p < .05$), and data integration ($\beta = .12, p < .05$).

DISCUSSION

The high positive correlation values and high incremental R^2 values validate that digital transformation is a key factor shaping technological innovations in engineering systems, which echoes the prevailing digital transformation and innovation literature (Vial, 2019; Verhoef et al., 2021). The result of the variance explained by the dimensions of digital transformation beyond control variables is consistent with previous claims that digital technologies are far more than just a supporting tool for innovation but rather are fundamentally transforming the process of innovation (Yoo et al., 2012; Nambisan et al., 2017).

The technological capabilities as the strongest individual predictor aligns with the dynamic capabilities view proposed by Warner and Wäger (2019) and Teece (2018) which indicates that the ability of an organization to create, acquire, internalize, and utilize digital technologies internally is more influential on the level of innovation achieved than the mere availability of infrastructure. The finding aligns with Kane et al. (2015) who also found that factors of organizations and capabilities, not technology adoption itself, primarily drive the difference between digitally mature and less mature organizations.

The relatively high importance of process digitization confirms results from Industry 4.0 studies that show that process and product innovation can only be continued by having access to real-time data and feedback loops from digitized and sensor-enabled processes (Lee et al., 2015; Tao et al., 2019). There are still relatively modest contributions from digital infrastructure and data integration, suggesting that these factors might rather be seen as prerequisite conditions for innovation rather than direct drivers of innovation, in line with Ghobakhloo's (2020) finding that infrastructure investment alone is not enough to create innovation benefits without complementing capability development. The results in this paper confirm the importance of process digitisation and technological capability development as well as of seeing the investments in infrastructure and data integration as means to an end.Together, these findings indicate that “enabling to innovation” efforts in the context of digital transformation investment in engineering organisations should focus on initiatives for building technological capability and on process digitisation efforts, while acknowledging that investments in infrastructure and data integration should be considered as means to an end, and not as an end in itself (Correani et al. 2020; Björkdahl 2020).

CONCLUSION AND RECOMMENDATIONS

All five digital transformation dimensions (digital infrastructure, data integration, process digitization, technological capabilities, and organizational readiness) significantly and substantially contribute to the prediction of technological innovation in engineering systems, with technological capabilities and process digitization being the strongest predictors of technological innovation, as found in this study. The results of this study validate that digital transformation can be considered as more of a multidimensional phenomenon, with its components having a differential impact on innovation outcomes in engineering. Given these results, engineering organizations should focus on investment in technological capability building, such as workforce digital skills and internal technology absorption capacity, along with process digitization efforts that integrate digital technologies into the core of engineering processes, as they are likely to have the highest return in terms of innovation outcomes. Additionally, it is recommended that the organizational readiness should be proactively developed by establishing leadership commitment and introducing change management in order to maximize the impact of digital infrastructure and data integration investments so that they are not underutilized but rather are the foundation of continued innovation capability. Future research could build on this explanatory model by employing longitudinal studies with causal explanations and include moderating variables such as organizational size, industry sector and digital leadership maturity that could vary and shape the relationship between digital transformation and technological innovation in different engineering contexts.

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