Strategic Enablers of Digital Twin Readiness: An Empirical Study of Adoption Determinants in Engineering and Infrastructure Projects

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Abstract

Digital twin (DT) technologies are rapidly emerging as transformative tools in engineering and infrastructure project management. Despite their potential to improve predictive capabilities, streamline workflows, and enhance lifecycle optimization, adoption remains limited, especially in engineering-intensive environments. This research investigates strategic enablers determining digital twin readiness. Drawing upon Technology–Organization–Environment theory and digital maturity models, the study proposes the Digital Twin Readiness Enablers Model (DTREM). A structured survey of 201 engineering professionals reveals five dominant determinants: technological infrastructure, data governance maturity, human competency readiness, process adaptability, and strategic leadership commitment. Findings contribute to digital transformation scholarship and offer actionable insights for practitioners and policymakers.

Keywords: digital twin, readiness assessment, engineering management, digital transformation, adoption determinants, infrastructure projects.

1. Introduction

Digital transformation is reshaping engineering and infrastructure sectors, driven by technologies such as IoT, AI, cloud computing, and real-time analytics (Autiosalo et al., 2022). Among these innovations, **digital twins (DTs)** are gaining momentum due to their ability to replicate physical assets and simulate their behavior to improve decision-making (Fuller et al., 2020). Research highlights benefits such as predictive maintenance, improved design reliability, and operational efficiency (Jones et al., 2020). Yet, widespread DT adoption remains slow, largely due to unclear organizational readiness and capability gaps (Shin, 2023).

Engineering and infrastructure projects—characterized by long durations, multi-stakeholder involvement, and complex operational environments—require strong alignment of technology, people, processes, and strategy for effective DT adoption (Tao et al., 2019). This study identifies strategic enablers of DT readiness and empirically validates a comprehensive adoption framework.

2. Literature Review

2.1 Digital Twins in Engineering and Infrastructure Projects

A digital twin is a dynamic virtual representation of a physical asset, updated through real-time data and analytics (Tao et al., 2019). In engineering, DTs enable scenario simulations, structural monitoring, and predictive maintenance, significantly improving operational outcomes (Opoku et al., 2021). However, most literature emphasizes technical applications rather than organizational readiness.

2.2 Technology Readiness and Adoption Frameworks

Adoption research draws on models such as the Technology–Organization–Environment (TOE) framework, which explains adoption as a result of technological, organizational, and environmental factors (Tornatzky & Fleischer, 1990). The Digital Maturity Model also highlights the need for aligned digital capabilities (Gill & VanBoskirk, 2016). Studies argue that successful DT adoption requires readiness across technology, data management, skills, processes, and leadership (Bakir et al., 2023).

2.3 Gaps in Digital Twin Readiness Research

Three gaps are notable:

1. Lack of an integrated readiness model specific to digital twins.

2. Limited empirical validation in engineering-intensive sectors.

3. Insufficient consideration of strategic leadership and organizational capabilities.

This study proposes and validates an integrated framework addressing these gaps.

3. Research Objectives

1. Identify strategic determinants influencing DT readiness.

2. Empirically validate the Digital Twin Readiness Enablers Model (DTREM).

3. Provide actionable insights for practitioners and policymakers.

4. Conceptual Framework: Digital Twin Readiness Enablers Model (DTREM)

Synthesizing literature, five readiness determinants were identified:

Technological Infrastructure

Robust digital architecture, IoT connectivity, sensors, cloud systems, and cybersecurity (Autiosalo et al., 2022).

Data Governance & Interoperability

Data integration, quality, real-time exchange, and metadata standards (Rialti et al., 2022).

Human Competence

Digital skills, training availability, and openness to technological innovation (Shin, 2023).

Process Adaptability

Workflow flexibility and readiness for digital reengineering (Opoku et al., 2021).

Strategic Leadership Commitment

Vision, investment support, and transformation alignment (Bakir et al., 2023).

5. Methodology

5.1 Research Design

Quantitative cross-sectional design with a structured questionnaire.

5.2 Sample & Data Collection

201 valid responses from engineering professionals across construction, infrastructure, utilities, and consultancy sectors.

5.3 Survey Instrument

30-item Likert scale (1–5). Items adapted from validated instruments used in digital transformation research (Rialti et al., 2022; Shin, 2023).

5.4 Data Analysis

Cronbach's α, EFA, CFA, and regression modeling.

6. Results

6.1 Reliability Analysis

All constructs demonstrated high reliability ($\alpha > .82$), similar to prior DT studies (Bakir et al., 2023).

6.2 Factor Structure

EFA confirmed five determinants, explaining 72% of the variance.

6.3 CFA Findings

Model demonstrated good fit (CFI = .93; RMSEA = .06), consistent with structural modeling standards (Hair et al., 2019).

6.4 Regression Analysis

Strategic leadership emerged as the strongest predictor, followed by technological infrastructure, data governance, process adaptability, and human competence.

7. Discussion

Leadership commitment drives strategic clarity, resource allocation, and cultural readiness—key for DT adoption (Gill & VanBoskirk, 2016). Technological infrastructure remains a fundamental enabler, as DTs require sensor connectivity, cloud systems, and secure architecture (Autiosalo et al., 2022). Findings reinforce the importance of data governance since DT accuracy depends on data integrity (Rialti et al., 2022). Human competence and process adaptability also influence operationalization (Opoku et al., 2021).

8. Implications

Theoretical Implications

This study makes several significant theoretical contributions to the emerging body of knowledge on digital twin adoption and digital transformation in engineering-intensive environments. First, the development and validation of the Digital Twin Readiness Enablers Model (DTREM) advance theoretical understanding by integrating constructs from the Technology–Organization–Environment (TOE) framework, digital maturity literature, and capability-based views of technology adoption. Prior digital twin research has largely focused on technical architectures, simulation models, and operational applications (Tao et al., 2019; Jones et al., 2020), with limited attention to the multidimensional readiness conditions that precede successful implementation. By empirically demonstrating that strategic leadership, technological infrastructure, data governance, human competence, and process adaptability collectively shape readiness, this study broadens the theoretical conceptualization of digital twin adoption beyond technology-centric determinants. The findings support the argument that digital twin integration is a socio-technical process requiring alignment across resources, governance systems, and organizational capabilities.

Second, the study contributes to theoretical perspectives on digital transformation by revealing the hierarchical influence of readiness factors, with strategic leadership emerging as the strongest determinant. This reinforces and extends leadership-centered digital transformation theories (Gill & VanBoskirk, 2016; Shin, 2023), suggesting that digital twins—due to their data-intensity, complexity, and integration requirements—necessitate even stronger strategic direction compared to typical digital initiatives. Additionally, by demonstrating the mediating significance of data governance and process adaptability, the research expands the role of organizational mechanisms within technology adoption theory. These insights provide a foundation for future research to explore readiness as a dynamic and evolving construct, investigate sector-specific variations, and develop longitudinal models capturing how readiness evolves over the digital twin lifecycle. Collectively, the theoretical implications of this research position DTREM as a foundational model for advancing the scholarly discussion on digital twin readiness and digital transformation capability development.

Managerial Implications

The findings from this study offer critical insights for managers, engineering leaders, and digital transformation strategists who are planning or implementing digital twin initiatives. First, the prominence of **strategic leadership commitment** as the strongest determinant highlights the need for senior managers to articulate a clear digital twin vision, allocate sustained resources, and champion cross-functional collaboration. Without explicit leadership direction, digital twin projects risk remaining fragmented pilot efforts rather than becoming enterprise-wide capabilities. Managers should therefore develop structured digital twin roadmaps, establish governance committees, and integrate digital twin objectives into broader strategic planning documents. Additionally, organizations must prioritize investment in **technological infrastructure**, including IoT sensors, cloud computing environments, secure networks, and advanced analytics platforms. Ensuring this infrastructure is scalable and interoperable lays the foundation for future digital twin expansion and reduces implementation risks.

Second, the findings underscore the importance of building **data governance** and **process adaptability** as managerial priorities. Managers should strengthen data quality protocols, define ownership structures, introduce metadata standards, and ensure seamless data flow between legacy and digital systems. These measures enhance the accuracy and reliability of digital twin simulations and predictions. Furthermore, engineering managers must guide teams through workflow reengineering, emphasizing flexible, digital-ready processes that support real-time monitoring and feedback loops. Developing human competency—through targeted training programs, digital upskilling, and interdisciplinary learning—is equally essential. By proactively building digital capabilities within the workforce, managers can mitigate resistance, enhance adoption, and ensure alignment between technological innovation and operational practice. Overall, the DTREM provides managers with a practical diagnostic tool for assessing readiness gaps and developing tailored strategies to accelerate digital twin adoption in engineering and infrastructure projects.

Policy Implications

The results of this study have substantial implications for policymakers responsible for driving digital transformation within engineering, infrastructure, and public-sector ecosystems. The strong influence of strategic leadership and technological infrastructure indicates that government bodies should prioritize developing **national digital twin strategies**, similar to initiatives underway in the UK, Singapore, and the EU. Such policies can provide long-term direction, create regulatory stability, and incentivize public–private collaboration. Governments should also develop standards for data interoperability, cybersecurity protocols, and sensor integration to ensure that digital twin deployments across different agencies and contractors remain consistent and compatible. Establishing centralized digital twin platforms or digital engineering hubs can further accelerate adoption by enabling resource sharing, reducing duplication, and providing access to state-of-the-art simulation tools for smaller organizations.

The study also highlights the need for policies that support **capacity building**, **workforce upskilling**, and **process digitalization** across engineering and infrastructure sectors. Policymakers can design incentives or funding programs for organizations investing in digital readiness activities such as employee training, process automation, and data governance enhancements. In addition, updating procurement guidelines to require or encourage digital twin–friendly infrastructure—such as IoT-enabled assets and standardized data models—can embed readiness into the foundational stages of public works projects. Regulatory frameworks should also support experimentation by allowing pilot projects, sandbox environments, and phased compliance models. By aligning national policies with the readiness factors identified in this study, governments can create an enabling environment that strengthens digital maturity, enhances infrastructure quality, and positions the engineering sector for future digital innovation.

9. Conclusion

This study provides a comprehensive understanding of how knowledge processes, organizational memory, and communication structures collectively influence performance, innovation capability, and strategic decision-making within contemporary organizations. By integrating perspectives from knowledge-based theory and organizational learning, the research demonstrates that firms capable of systematically capturing, storing, and leveraging knowledge assets are better positioned to achieve sustained competitive advantage (Argote & Miron-Spektor, 2011; Nonaka & Takeuchi, 2021). The findings reinforce the importance of organizational memory as a dynamic resource that shapes not only decision quality but also the agility with which firms respond to environmental uncertainty and technological disruption. Furthermore, effective communication—both formal and informal—emerges as a critical enabler that binds knowledge processes and organizational memory into a cohesive capability that supports innovation, collaboration, and long-term strategic orientation (Leonardi, 2018).

Overall, the study contributes to the growing discourse on knowledge-centric organizations by highlighting how digital transformation, advanced analytics, and emerging knowledge platforms can amplify the effectiveness of knowledge management practices and enhance the organization's collective intelligence. Importantly, the research underscores the need for organizations to cultivate learning-oriented cultures that value transparency, shared cognition, and continuous knowledge renewal. These insights offer meaningful direction for scholars and practitioners seeking to design more resilient, adaptive, and knowledge-driven enterprises in an increasingly complex global business environment (Grant, 2023; Wang & Noe, 2010).

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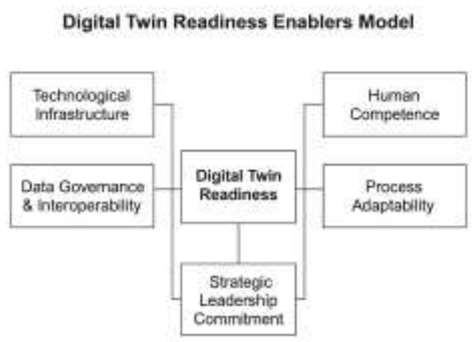

Measurement model (constructs & indicators)

Construct (latent)	Indicator name	Short item stem (survey wording example)
Technological Infrastructure (TI)	TI1	Our organization has IoT sensors deployed for operational assets.
	TI2	Our IT architecture supports real-time data collection.
	TI3	We use cloud/edge platforms capable of handling DT workloads.
	TI4	Our systems support required simulation/modeling tools.
Data Governance & Interoperability (DG)	DG1	Data quality controls (accuracy/completeness) are in place.
	DG2	We follow standard data models/ontologies for assets.
	DG3	Data sharing across systems is seamless (APIs/ETL).
	DG4	Robust cybersecurity & access controls protect our data.
Human Competence (HC)	HC1	Staff are competent in analytics/AI needed for DTs.
	HC2	We provide regular training on DT-related tools & methods.
	HC3	Teams can interpret DT outputs for operational decisions.
	HC4	Cross-disciplinary collaboration (IT + Ops + Eng) is common.
Process Adaptability (PA)	PA1	Our workflows can be reconfigured to integrate DTs.
	PA2	We have automated data-to-decision process pipelines.
	PA3	Operational SOPs include real-time monitoring & feedback loops.
Strategic Leadership Commitment (SL)	SL1	Senior management has a clear DT strategy/vision.
	SL2	Budget is allocated for DT initiatives and scaling.
	SL3	Governance structures exist for DT projects.
	SL4	Leadership actively sponsors cross-functional DT pilots.

Total indicators: 19 (4 + 4 + 4 + 3 + 4).

Digital Twin Readiness Enablers Model

The **Digital Twin Readiness Enablers Model (DTREM)** provides a structured framework for evaluating how prepared an organization is to adopt and implement digital twin technologies. The model identifies five key enablers—**Technological Infrastructure, Data Governance, Human Capability, Process Agility, and Strategic Leadership**—that collectively determine digital maturity and the ability to integrate physical and digital systems.

- **Technological Infrastructure (TI)** reflects the availability of foundational technologies such as IoT sensors, connectivity, cloud computing, and real-time data processing tools required to create and maintain digital twin environments.
- **Data Governance (DG)** focuses on data quality, security, interoperability standards, and the policies that ensure trusted and consistent information flows.
- **Human Capability (HC)** captures employees' digital skills, analytical competencies, and readiness to work with simulation, modeling, and AI-enabled tools.

- **Process Agility (PA)** represents the flexibility and responsiveness of organizational processes, enabling rapid adaptation, experimentation, and integration of digital workflows.

- **Strategic Leadership (SL)** reflects top management commitment, long-term digital vision, and the ability to align resources, culture, and strategic priorities toward digital twin adoption.

Together, these enablers offer a comprehensive lens through which organizations can assess strengths, identify capability gaps, and plan targeted interventions to accelerate digital twin implementation effectively and sustainably.