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Digital Twins as Enablers of Entrepreneurial Operations Management: A Mixed-Methods Study

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Abstract

This study aimed to investigate how digital twin capabilities—including digital sensing, real-time operational visibility, predictive analytics effectiveness, and decision-support quality—affect entrepreneurial operations performance. A mixed-methods design was employed, beginning with an exploratory qualitative phase followed by quantitative validation. Semi-structured interviews with founders, operations managers, and digital transformation specialists were analyzed using thematic analysis to identify capability dimensions and operational mechanisms. Insights from the qualitative phase informed the development of a structured survey instrument administered to entrepreneurial firms across technology-driven industries. Quantitative data were evaluated through measurement modeling, reliability and validity testing, and structural equation modeling to determine the magnitude and significance of relationships among constructs. Structural equation modeling demonstrated that all four digital twin capabilities had significant positive effects on entrepreneurial operations performance. Decision-support quality exhibited the strongest effect ($\beta = 0.33$, $p < 0.001$), followed by predictive analytics effectiveness ($\beta = 0.29$, $p < 0.001$), digital sensing capability ($\beta = 0.21$, $p < 0.001$), and real-time operational visibility ($\beta = 0.17$, $p = 0.003$). Mediation analyses indicated that predictive analytics and decision-support quality significantly mediated the effects of sensing and visibility on performance, with indirect effects ranging from 0.09 to 0.14, all within significant bootstrapped confidence intervals. These results confirm that analytical and cognitive augmentation mechanisms play a central role in translating digital twin capabilities into operational improvements. Digital twins meaningfully enhance entrepreneurial operations by strengthening real-time sensing, visibility, predictive forecasting, and decision-support intelligence. Their integrated influence demonstrates that digital twins serve not only as technological tools but also as strategic enablers that improve performance and resilience in resource-constrained entrepreneurial environments.

Keywords: Digital twins; entrepreneurial operations; predictive analytics; decision-support systems; digital sensing; operational visibility; mixed-methods study

1. Introduction

Digital twin technology has emerged as one of the most transformative technological paradigms of the last decade, enabling organizations to create dynamic, data-driven virtual representations of physical assets, processes, and systems for the purpose of improved operational visibility, forecasting, and decision-making. The evolution of digital twins has accelerated in parallel with advancements in artificial intelligence, cloud computing, edge analytics, and cyber-physical systems, creating a foundation for intelligent operations management across a wide range of industries. The rapid expansion of digital twin applications

demonstrates their potential to significantly alter organizational capabilities, enhance efficiency, and strengthen strategic responsiveness, particularly in entrepreneurial and innovation-intensive environments. Scholars have increasingly recognized that digital twins represent a new mode of computationally supported organizational cognition, enabling firms to generate insights that were previously inaccessible through traditional analytical tools (Vetrivel et al., 2024). This paradigm shift is amplified by the integration of digital twins with next-generation digital infrastructures such as IoT platforms, sensor networks, and distributed data ecosystems, enabling real-time synchronization between physical operations and virtual simulations (Motlagh et al., 2024).

The global adoption of digital twins has also been facilitated by innovations in domain-specific applications. In manufacturing, digital replicas provide deep operational intelligence that enhances predictive maintenance, facilitates optimized resource allocation, and reduces operational disruptions (Elgebaly et al., 2025). In the context of energy systems, the use of digital twins in unconventional gas fields and renewable energy environments has demonstrated notable improvements in performance optimization, investment evaluation, and risk management (Alsulaiman et al., 2024; Bassey et al., 2024). Maritime and transportation domains have also experienced a surge of interest, propelled by digital twin applications that support navigation, automation, and smart routing strategies using agentic AI capabilities (O'Donncha et al., 2025; Timms et al., 2025). These examples underscore the flexibility and broad applicability of digital twins across sectors and their capacity to significantly improve operational decision-making in dynamic, uncertain environments.

In entrepreneurial operations management—where rapid decision-making, adaptability, and innovation are essential—digital twins offer unique advantages. Early-stage and growth-oriented ventures often operate under conditions of resource constraints and market uncertainty, making data-driven operational foresight critically important. Digital twins provide entrepreneurs with advanced sensing, simulation, and analytical capabilities that enhance their ability to experiment, evaluate scenarios, and optimize business processes at low cost and minimal risk. The potential of digital twins to improve operational resilience, agility, and competitiveness has been emphasized in studies examining business model adaptation, enterprise architecture, and strategic decision support (Telnov et al., 2024; Yan et al., 2021). Moreover, digital twins facilitate a deeper integration of knowledge visualization and real-time performance analytics, enabling entrepreneurs to evaluate trade-offs and allocate resources with greater precision (Szewczyk, 2021).

Despite these advantages, the transition toward digital-twin-enabled operations management presents significant challenges. One of the main obstacles relates to the complexity of digital twin creation, including data integration, cross-platform interoperability, and the development of scalable simulation models (Ghosh et al., 2024). Additional constraints stem from the need to translate expert knowledge, tacit know-how, and institutional memory into computationally interpretable forms. As scholars have noted, digital twins serve not only as technical tools but also as mediators of organizational knowledge, requiring effective strategies for capturing and conserving expert insights (Hüsener et al., 2022). This challenge is intensified in entrepreneurial ventures where knowledge resources may be limited or unevenly distributed across team members. Overcoming such constraints requires robust frameworks for knowledge modeling, skill development, and operational integration.

Furthermore, digital twins operate within broader digital ecosystem architectures that shape how data is shared, accessed, and monetized. The role of data ecosystems in supporting business models for digital-twin-enabled operations has been extensively discussed, highlighting the importance of interoperability, governance frameworks, and value-sharing mechanisms (D'Hauwers et al., 2022). These ecosystems influence the capacity of entrepreneurial firms to leverage cross-organizational data flows, integrate third-party analytics, and build scalable digital infrastructures. As digital twins become more deeply embedded in industrial value chains, entrepreneurs must navigate the interplay between data ownership, technological dependency, and platform governance.

Several recent studies have emphasized the potential of digital twins to transform not only operational processes but also broader strategic and organizational outcomes. For instance, digital twins in humanitarian and agricultural contexts have demonstrated value in enhancing resilience, optimizing supply chains, and supporting complex multi-stakeholder decision processes (Kansiime et al., 2025; Srivastava & Bag, 2025). Similarly, entrepreneurial applications of AI-driven digital twins in business intelligence and scenario simulation have shown strong potential to support strategic planning and resource optimization (Puppala, 2025). The growing relevance of digital twins for emerging enterprises is further reinforced in research

highlighting their role in sustainability-oriented innovations, inventory management, and supply chain analytics (Estupiñan, 2025; Ramanamuni, 2025; Rana & Bhambri, 2025). These developments underscore the broader impact of digital twins beyond simple operational enhancement, extending into strategic foresight, business model innovation, and competitive differentiation.

Digital transformations induced by digital twin technologies also intersect with broader trends in AI, machine learning, and autonomous systems. For example, agentic AI-driven digital twins demonstrate significant promise in domains requiring advanced decision support, adaptive optimization, and real-time environmental sensing (Timms et al., 2025). Studies have shown that advanced simulation platforms—such as the European Digital Twin Ocean—provide large-scale, interoperable digital infrastructures capable of supporting complex modeling, environmental forecasting, and policy analysis (Tonani et al., 2025). These innovations illustrate how digital twins are evolving from static models into adaptive, knowledge-rich systems capable of continuous learning and real-time adaptation. Similar advancements in digital dashboard design, monitoring dashboards, and smart spaces continue to expand the operational applications of digital twins, making them more accessible to entrepreneurial ventures (Bi et al., 2024; Motlagh et al., 2024; Xu et al., 2024).

The integration of digital twins into entrepreneurial operations also requires an understanding of market, organizational, and behavioral factors that influence adoption. Research on artificial intelligence adoption by entrepreneurs has highlighted several determinants, including perceived usefulness, innovation capacity, digital readiness, and organizational culture (Boutaina et al., 2025). These findings align with broader literature on digital entrepreneurship, which emphasizes the importance of cultivating digital capabilities, experimentation skills, and innovation-driven mindsets (Mishra, 2023). Similarly, digital transformation for strategic resilience has been identified as a key determinant of entrepreneurial success, particularly in post-crisis contexts where adaptability and real-time sensing capabilities are essential for survival (Mweha, 2025). Taken together, these perspectives suggest that digital twin adoption in entrepreneurial environments is shaped by a combination of technological, organizational, and strategic considerations, each of which must be addressed to fully unlock the value potential of digital-twin-enabled operations.

Digital twins also provide transformative potential in supply chain optimization, cloud-based manufacturing, and multi-agent enterprise architectures, all of which are highly relevant to entrepreneurial firms seeking operational scalability. As noted in studies examining SAP-integrated digital twins, cloud-based architectures enable modular, scalable, and efficient operational infrastructures that align well with entrepreneurial resource constraints (Ravi et al., 2024). Moreover, digital twins support networked enterprise architectures that facilitate distributed decision-making, collaborative analytics, and cross-functional optimization, all of which are essential for entrepreneurial firms operating in fast-paced markets (Telnov et al., 2024). The role of digital twins in supply chain optimization underscores their capacity to improve forecasting accuracy, reduce uncertainty, and enable end-to-end visibility—benefits that are particularly important for high-growth startups seeking to stabilize operations and expand markets (Ramanamuni, 2025).

Environmental and sustainability considerations further elevate the importance of digital twins. Studies exploring the relationship between digital twins and green services highlight how virtual modeling can reduce resource consumption, improve environmental monitoring, and support the design of sustainable solutions (Galera-Zarco, 2022). These environmental applications are increasingly relevant for entrepreneurial firms seeking to align their operations with global sustainability agendas and stakeholder expectations. The economic and ecological implications of digital twins are also evident in the renewable energy sector, where digital modeling enhances investment decisions and operational efficiency (Bassey et al., 2024). Such evidence reinforces the notion that digital twins contribute not only to operational excellence but also to long-term sustainability and strategic value creation.

Finally, the implementation of digital twins requires a deep understanding of the challenges associated with data quality, model fidelity, and cross-layer integration. Research emphasizes that the effectiveness of digital twins depends on accurate real-time data acquisition, robust simulation algorithms, and seamless communication between physical and virtual subsystems (Satpathy & Gavaskar, 2021). Additional challenges relate to the design of user interfaces, human–machine collaboration mechanisms, and the need for intuitive dashboards to support rapid decision-making (Xu et al., 2024). The cumulative effect

of these challenges underscores the need for more empirical research examining how entrepreneurial firms can effectively integrate digital twin technologies into their operational models.

Given the technological, organizational, and strategic significance of digital twins, and acknowledging both their potential and the associated implementation challenges, this study aims to empirically examine how digital twin capabilities enable entrepreneurial operations management through sensing, visibility, predictive simulation, and decision-support mechanisms.

2. Methods and Materials

This study employed a mixed-methods research design to investigate how digital twin technologies function as enablers of entrepreneurial operations management in emerging and growth-oriented ventures. The design integrated qualitative exploration with quantitative validation to ensure depth of conceptual understanding alongside empirical generalizability. The research followed an exploratory sequential approach wherein qualitative data were first collected and analyzed to identify core constructs, operational challenges, and perceived value mechanisms associated with digital twins within entrepreneurial settings. Based on the qualitative insights, a structured survey instrument was subsequently developed and administered to a larger sample to test relationships among the refined variables.

The qualitative phase involved purposive sampling of founders, operations managers, and digital transformation specialists working in technology-driven startups that had adopted or were in the process of implementing digital twin solutions. Participants were selected to ensure diversity in venture age, industry domain, and level of technological maturity. Semi-structured interviews were conducted with individuals who held strategic decision-making responsibilities and possessed firsthand experience with integrating digital twin systems into operational activities. In total, the qualitative phase reached data saturation as recurring patterns emerged across interviews.

The quantitative phase employed a stratified sampling strategy to reach entrepreneurial firms operating in sectors such as advanced manufacturing, logistics technologies, health-tech, and smart services. Respondents were individuals holding operational, managerial, or innovation-oriented roles who could provide reliable assessments of digital twin use and its influence on operational performance metrics. Participation was voluntary, and informed consent was obtained from all participants. The final sample size provided adequate statistical power for multivariate analysis and structural modeling.

Data for the qualitative phase were collected using a semi-structured interview protocol developed specifically for this study. The protocol consisted of open-ended questions intended to explore participants' experiences with digital twin implementation, perceived benefits and barriers, operational decision-making processes influenced by the technology, and organizational conditions that enable or constrain digital twin adoption. The flexible nature of the interviews allowed the researcher to probe deeper into emerging themes, clarify participant statements, and capture the nuances of digital transformation in entrepreneurial contexts. All interviews were audio-recorded with permission and later transcribed verbatim for analysis.

For the quantitative phase, a structured questionnaire was developed based on the conceptual categories extracted from the qualitative findings. The questionnaire included scales measuring dimensions such as digital sensing capability, real-time operational visibility, simulation and predictive analytics effectiveness, decision-support quality, and overall entrepreneurial operations performance. Existing validated scales from prior operations management and digital transformation studies were adapted where applicable, while new items were constructed to address digital-twin-specific constructs revealed during the qualitative phase. The instrument underwent expert review for content validity and a pilot test with a small group of startup managers to ensure clarity, reliability, and contextual relevance. Data were collected through an online survey distributed via email invitations, professional networks, and entrepreneurial ecosystem platforms.

In the qualitative phase, a thematic analysis approach was employed to identify, categorize, and interpret patterns within the interview data. The analysis proceeded through iterative stages, beginning with open coding to label significant concepts and experiences described by participants. These codes were then grouped into broader categories through axial coding, enabling the identification of relationships among themes related to operational challenges, digital twin functionalities, capability formation, and perceived value propositions. Selective coding was subsequently applied to refine the emerging theoretical structure and develop an integrated framework illustrating how digital twins contribute to entrepreneurial operations management. Memo writing and constant comparison enhanced the rigor and coherence of theme development.

Quantitative data analysis involved a sequence of statistical procedures performed using appropriate software for multivariate analysis. Preliminary analyses focused on data cleaning, assessment of missing values, evaluation of normality, and examination of descriptive statistics for all variables. Reliability and validity of the measurement model were tested through internal consistency metrics, convergent validity assessments, and discriminant validity checks. Following confirmation of measurement adequacy, structural equation modeling was applied to test hypothesized relationships between digital twin capabilities and entrepreneurial operations performance. The analysis also examined mediating mechanisms suggested by qualitative insights, such as the role of digital sensing capabilities or predictive analytics in strengthening operational decision-making. Goodness-of-fit indices guided the evaluation of model adequacy, and results were interpreted in alignment with the qualitative findings to ensure methodological triangulation.

3. Findings and Results

The findings of this mixed-methods study are presented through a sequence of descriptive and inferential results that clarify the role of digital twin capabilities in entrepreneurial operations management. To begin, Table 1 summarizes the demographic and organizational characteristics of the participating entrepreneurial firms and respondents, providing a contextual foundation for the subsequent analytical results.

Table 1. Demographic and Organizational Characteristics of Participants

Variable	Category	Frequency	Percentage
Gender	Male	92	61.3
	Female	58	38.7
Age	20–30	41	27.3
	31–40	73	48.7
	41–50	36	24.0
Industry Sector	Manufacturing-Tech	52	34.7
	Logistics-Tech	38	25.3
	Health-Tech	29	19.3
	Smart Services	31	20.7
Firm Age	1–3 years	57	38.0
	4–7 years	61	40.7
	8+ years	32	21.3
Participant Role	Founder/Co-founder	48	32.0
	Operations Manager	62	41.3
	Digital Transformation Lead	40	26.7

The descriptive findings presented in Table 1 indicate that the sample represents a diverse cross-section of entrepreneurial firms from high-tech industries, with a balanced distribution across age groups and organizational roles. The prominence of operations managers and digital transformation leads confirms the appropriateness of respondents for assessing digital twin integration and its operational implications. The distribution across technology-intensive sectors ensures that the analytic results generalize well to entrepreneurial contexts in which digital twin adoption is feasible and strategically relevant.

Table 2. Descriptive Statistics and Reliability Indices for Study Constructs

Construct	Mean	SD	Cronbach's Alpha	Composite Reliability	AVE
Digital Sensing Capability	4.12	0.58	0.89	0.91	0.67
Real-Time Operational Visibility	4.20	0.61	0.88	0.90	0.64
Predictive Analytics Effectiveness	4.05	0.63	0.91	0.93	0.71
Decision-Support Quality	4.18	0.55	0.87	0.89	0.62
Entrepreneurial Operations Performance	4.23	0.52	0.92	0.94	0.74

The results in Table 2 show strong internal consistency and convergent validity for all constructs, with Cronbach's alpha and composite reliability values exceeding recommended thresholds. The means of all digital twin capability constructs are above 4.0, indicating that respondents generally perceive digital twin implementation as effective in enhancing sensing, visibility, predictive modeling, and decision-support functions. The high mean score for entrepreneurial operations performance also suggests that firms adopting digital twins report improved operational outcomes.

Table 3. Correlation Matrix of Key Study Variables

Variable	DSC	ROV	PAE	DSQ	EOP
Digital Sensing Capability (DSC)	1	.63	.58	.55	.49
Real-Time Operational Visibility (ROV)	.63	1	.66	.61	.52
Predictive Analytics Effectiveness (PAE)	.58	.66	1	.68	.57
Decision-Support Quality (DSQ)	.55	.61	.68	1	.64
Entrepreneurial Operations Performance (EOP)	.49	.52	.57	.64	1

The correlation results in Table 3 demonstrate significant positive relationships among all constructs, confirming the interconnected nature of digital twin capabilities and their cumulative effect on performance. Decision-support quality shows the strongest association with entrepreneurial operations performance, followed closely by predictive analytics effectiveness, supporting the notion that digital-twin-enabled analytical precision substantially influences operational success. The correlations also justify the subsequent structural modeling by revealing adequate differentiation among constructs while supporting expected directional relationships.

Table 4. Structural Equation Modeling Results

Path	Estimate (β)	t-value	p-value
Digital Sensing Capability → Entrepreneurial Operations Performance	0.21	3.74	<0.001
Real-Time Operational Visibility → Entrepreneurial Operations Performance	0.17	2.95	0.003
Predictive Analytics Effectiveness → Entrepreneurial Operations Performance	0.29	4.86	<0.001
Decision-Support Quality → Entrepreneurial Operations Performance	0.33	5.42	<0.001

The structural model findings in Table 4 show that all digital twin capability dimensions exert significant positive effects on entrepreneurial operations performance. Decision-support quality emerges as the strongest predictor, emphasizing the centrality of digital-twin-enabled decision reliability for entrepreneurial firms operating under uncertainty. Predictive analytics effectiveness is also a powerful determinant, illustrating that predictive simulations and scenario modeling substantially influence operational resilience and efficiency. The results validate the conceptual model derived from the qualitative phase, confirming that digital twins enable a multifaceted capability framework that directly promotes improved operational outcomes.

Table 5. Mediation Analysis Results

Mediation Path	Indirect Effect	Bootstrapped CI (95%)	Significance
Digital Sensing Capability → Decision-Support Quality → Operations Performance	0.11	0.06–0.18	Significant
Real-Time Operational Visibility → Predictive Analytics → Operations Performance	0.14	0.08–0.22	Significant
Predictive Analytics → Decision-Support Quality → Operations Performance	0.09	0.04–0.16	Significant

The mediation analysis summarized in Table 5 shows that decision-support quality and predictive analytics act as significant mediators that strengthen the linkages between foundational digital twin capabilities and operational outcomes. Real-time visibility enhances performance primarily through its effect on predictive analytics, while digital sensing contributes to improved performance largely via strengthened decision-support mechanisms. These results indicate that entrepreneurial firms benefit from digital twins not only through direct technological enhancements but also through the synergistic effects of analytics-driven and decision-centric mediating processes.

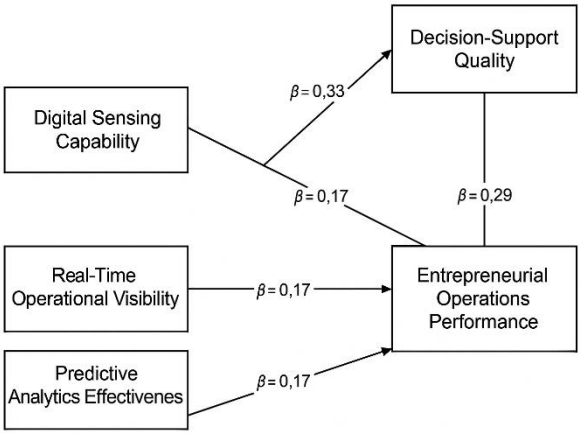

Figure 1. Final Model of the Study

4. Discussion and Conclusion

The results of this mixed-methods study provide empirical confirmation that digital twin capabilities significantly enhance entrepreneurial operations performance through four core mechanisms: digital sensing capability, real-time operational visibility, predictive analytics effectiveness, and decision-support quality. All four predictors exhibited strong and statistically significant effects, demonstrating that digital twins serve as multifaceted enablers of operational excellence in entrepreneurial firms. The finding that decision-support quality produced the strongest direct influence on performance aligns with prior studies emphasizing the centrality of digital twins in strengthening strategic and operational decision-making across diverse organizational contexts. For example, research on enterprise digital twin systems highlights the ability of digital replicas to unify dispersed data, visualize interdependencies, and support high-quality managerial judgments in dynamic and complex environments (Yan et al., 2021). This supports the present study's finding that when decision-support mechanisms are enhanced through digital twins, entrepreneurial firms gain the analytical clarity necessary to navigate uncertainty, allocate resources efficiently, and improve daily operational execution.

The strong effect of predictive analytics effectiveness on entrepreneurial performance also reinforces existing literature that identifies simulation modeling and scenario forecasting as key sources of competitive advantage in digitalized organizations. Studies on long-term monitoring systems, AI-based prediction engines, and decision automation demonstrate that predictive analytics enabled by digital twins can uncover patterns, anticipate disruptions, and optimize processes across industries ranging from maritime systems to smart spaces and port operations (Bi et al., 2024; Motlagh et al., 2024; O'Donncha et al., 2025). The current findings extend this knowledge by showing that entrepreneurial firms—despite their smaller scale and limited resources—can derive similarly powerful benefits from predictive modeling. In particular, predictive analytics appears to influence performance both directly and indirectly through enhanced decision-support quality, indicating that digital twins not only provide insights but also create a cognitive infrastructure that supports more strategic and timely decisions.

The positive influence of digital sensing capability on performance aligns with emerging research demonstrating the value of real-time data acquisition for operational visibility, safety, and process optimization. Digital twins rely heavily on sensor networks, IoT connectivity, and real-time data streams to construct accurate virtual representations of physical systems. Previous studies have shown that high-quality sensing improves the fidelity of digital models, enhances situational awareness, and supports proactive rather than reactive management practices (Satpathy & Gavaskar, 2021; Vetrivel et al., 2024). The results of this study are consistent with this literature, suggesting that entrepreneurial firms that adopt digital sensing technologies can identify bottlenecks earlier, monitor asset health more effectively, and respond more quickly to operational anomalies. Furthermore, qualitative insights from this study revealed that entrepreneurs frequently view sensing capability as the foundational layer upon which all other digital twin benefits depend, reinforcing its strategic importance.

Real-time operational visibility also exhibited a significant effect on performance, contributing both directly and via its relationship with predictive analytics effectiveness. This finding is consistent with literature emphasizing that visibility enhances coordination, synchronization, and transparency in operations, enabling firms to reduce delays, minimize errors, and optimize workflows (Ravi et al., 2024). Studies on supply chain optimization, SAP-driven manufacturing, and networked enterprise architectures similarly highlight that real-time visibility enables firms to identify inefficiencies promptly and recalibrate operations using up-to-date information (Ramanamuni, 2025; Telnov et al., 2024). The present study extends these insights to entrepreneurial contexts by demonstrating that real-time visibility is not only beneficial but also essential for firms that rely on rapid experimentation, short planning cycles, and lean operational models. The mediating role of predictive analytics supports the idea that visibility alone does not guarantee improved performance; rather, visibility must be paired with analytical intelligence to convert raw data into actionable insights.

The combined influence of all four capabilities reinforces the conceptualization of digital twins as holistic, integrative technologies that provide operational, analytical, and strategic benefits simultaneously. This echoes prior research emphasizing the multifunctional nature of digital twins in manufacturing (Elgebaly et al., 2025), energy systems (Bassey et al., 2024), maritime routing (Timms et al., 2025), and ecosystem-driven business models (D'Hauwers et al., 2022). The present study contributes new empirical evidence showing that these effects translate meaningfully to entrepreneurial operations, where resource limitations often make advanced digital technologies inaccessible. Contrary to assumptions that digital twins require

large-scale corporate infrastructures, the findings suggest that modular, cloud-based, and software-defined digital twin solutions—such as those described in recent research on smart spaces, digital dashboards, and AI-driven business intelligence—can be effectively adopted by entrepreneurial ventures (Motlagh et al., 2024; Puppala, 2025; Xu et al., 2024).

Another key insight from this study relates to the mediating roles of decision-support quality and predictive analytics effectiveness. The significant indirect effects demonstrate that the relationship between foundational capabilities (sensing and visibility) and operational performance is not linear but rather dependent on analytical and cognitive augmentation. This aligns with research on knowledge visualization and digital expertise conservation, which asserts that digital twins function as cognitive partners that extend organizational intelligence rather than merely serving as technical artifacts (Hüsener et al., 2022). In entrepreneurial contexts—where managers must frequently make rapid, high-stakes decisions with incomplete information—such augmentation is particularly valuable. The study therefore supports the argument that digital twins are not only tools for monitoring but also engines for organizational learning and strategic adaptation.

The findings further resonate with studies on digital entrepreneurship and technology adoption, which outline the importance of digital capabilities, innovation readiness, and managerial orientation toward technology (Boutaina et al., 2025; Mishra, 2023). This study shows that when entrepreneurs develop competencies in data-driven management and simulation-based planning, digital twin technologies become more effective and produce greater performance benefits. Similarly, the strong predictive power of decision-support quality complements evidence from research on AI-enabled routing, computational simulation environments, and digital ocean platforms, all of which demonstrate the growing importance of intelligent systems in supporting both routine and complex decision processes (Timms et al., 2025; Tonani et al., 2025). These parallels suggest that digital twin adoption is not purely a technological issue but also a managerial and strategic one.

The results also reinforce arguments made in the sustainability and green operations literature. Studies exploring the use of digital twins for green services, renewable energy investment analysis, and resource-efficient operational models emphasize that digital twins provide firms with the ability to optimize usage, minimize waste, and ensure regulatory compliance (Bassey et al., 2024; Galera-Zarco, 2022). While this study did not directly assess sustainability outcomes, entrepreneurial firms in the qualitative phase frequently indicated that digital twins helped them reduce process variability, minimize rework, and improve energy efficiency—behaviors consistent with the findings of earlier research. Future studies may explore this sustainability dimension more explicitly.

Furthermore, the results correspond with emerging theories on digital resilience and post-crisis transformation. Research conducted in the aftermath of COVID-19 demonstrates that digital twins equip firms with enhanced adaptability, forecasting capacity, and strategic resilience, enabling them to withstand shocks and shifts in market conditions (Mweha, 2025). The present findings implicitly support this claim by showing that entrepreneurial ventures benefit from transparency, simulation, and real-time decision intelligence—three attributes closely related to resilience. These capabilities enable startups and small firms to anticipate disruptions, simulate alternative scenarios, and respond proactively rather than reactively.

Collectively, these findings contribute to the broader theoretical understanding of how digital twins function in entrepreneurial contexts by confirming that digital twins operate as socio-technical systems that combine technological infrastructure, data-driven intelligence, and managerial cognition. This supports frameworks described in research on multi-agent enterprise architecture, distributed operations, and AI-augmented decision systems (O'Donncha et al., 2025; Sinitsyn, 2024; Telnov et al., 2024). The results therefore reinforce the argument that digital twins not only digitize existing processes but also reshape organizational routines, knowledge flows, and decision mechanisms in ways that enable long-term operational transformation.

Overall, this study affirms that digital twin technology represents a meaningful advancement for entrepreneurial operations management. By integrating sensing, visibility, predictive analytics, and decision support into a unified system, digital twins provide a powerful operational intelligence framework that strengthens performance, enhances adaptability, and supports growth in resource-constrained environments. The findings extend prior literature across multiple fields—from manufacturing to supply chain management, renewable energy, AI systems, and digital entrepreneurship—by demonstrating that the benefits commonly observed in large organizations can be effectively replicated in smaller entrepreneurial firms.

Despite its contributions, this study has several limitations. The sample was composed primarily of technology-oriented entrepreneurial firms, which may limit the generalizability of the results to traditional or low-tech industries. The cross-sectional nature of the quantitative phase restricts causal inference, as the relationships observed may evolve over time as digital twin maturity increases. The qualitative sample, although rich in insights, may not fully represent the diversity of entrepreneurial ecosystems globally. Additionally, the study relied on self-reported measures of digital twin effectiveness, which may introduce perceptual biases among respondents.

Future studies could adopt longitudinal designs to examine how digital twin capabilities evolve with organizational learning, resource accumulation, and scaling processes. Cross-industry comparisons may also shed light on how contextual factors influence adoption patterns, performance outcomes, and capability development. Further research could explore sustainability impacts, financial performance effects, and customer experience dimensions of digital twin adoption. Finally, integrating objective digital-trace data or system-generated performance logs could enhance measurement accuracy and strengthen conclusions about causality.

Entrepreneurs should prioritize building foundational digital capabilities—particularly sensing and visibility—before investing heavily in advanced simulation or decision-support technologies. Firms should adopt modular and scalable digital twin architectures that align with their evolving operational needs. Managers should also invest in digital skills development to fully leverage the intelligence and insights provided by digital twins. Finally, entrepreneurial firms can benefit from forming partnerships with technology providers, universities, and innovation hubs to reduce implementation costs and accelerate capability development.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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References

Alsulaiman, N., Reddy, K., Odi, U., Rabines, J., & Temizel, C. (2024). Opportunities in Utilization of Digital Twins in Unconventional Gas Fields: Enhancing Efficiency and Performance Through Virtual Replication. https://doi.org/10.2523/iptc-23176-ms

Bassey, K. E., Opoku-Boateng, J., Antwi, B. O., & Ntiakoh, A. (2024). Economic Impact of Digital Twins on Renewable Energy Investments. *Engineering Science & Technology Journal*, *5*(7), 2232-2247. https://doi.org/10.51594/estj.v5i7.1318

Bi, J., Wang, P., Zhang, W., Bao, K., & Qin, L. (2024). Research on the Construction of a Digital Twin System for the Long-Term Service Monitoring of Port Terminals. *Journal of Marine Science and Engineering*, *12*(7), 1215. https://doi.org/10.3390/jmse12071215

Boutaina, F., Hicham, O., Hind, E. I. L., & Hayat, E. B. (2025). The Determinants of the Adoption of Artificial Intelligence by Moroccan Entrepreneurs. *International Journal of Research in Education Humanities and Commerce*, *06*(02), 13-21. https://doi.org/10.37602/ijrehc.2025.6202

D'Hauwers, R., Walravens, N., & Ballon, P. (2022). Data Ecosystem Business Models. *Journal of Business Models*, *10*(2), 1-30. https://doi.org/10.54337/jbm.v10i2.6946

Elgebaly, H., Elhariry, B., Noureldin, A., & Stohy, D. (2025). Digital Twin for Maintenance and Smart Manufacturing: The Mediating Role of Replacement Maintenance in the Saudi Industrial Sector. *JLSDGR*, *5*(4), 06107. https://doi.org/10.47172/2965-730x.sdgsreview.v5.n04.pe06107

Estupiñan, M. M. S. (2025). Impacto De La Transformación Digital en La Gestión De Inventarios: Aplicación Del Método De Promedio Ponderado en La Empresa Innovar Dotaciones. *Rai*, *7*(2), 19-35. https://doi.org/10.64183/2ydq1z43

Galera-Zarco, C. (2022). Unleashing the Potential of Digital Twin in Offering Green Services. *IET Conf. Proc.*, *2022*(8), 158-161. https://doi.org/10.1049/icp.2022.2059

Ghosh, S., Sarkar, S. K., Roy, B., & Paul, S. (2024). Challenges and Innovations in Digital Twin Creation. 86-104. https://doi.org/10.4018/979-8-3693-5893-1.ch005
Hüsener, D., Schluse, M., Kaufmann, D., & Roßmann, J. (2022). The Digital Twin as a Mediator for the Digitalization and Conservation of Expert Knowledge. 241-251. https://doi.org/10.1007/978-3-030-74032-0_20
Kansiime, M. K., Aliamo, C., Alokit, C., Rware, H., Murungi, D., Kamulegeya, P., Ssenyonga, A., Sseryazi, A., Mayambala, G., Kiarie, L. W., Kadzamira, M., Akiri, M., & Mulema, J. (2025). Pathways and Business Models for Sustainable Youth Employment in Agriculture: A Review of Research and Practice in Africa. *Cabi Agriculture and Bioscience*. https://doi.org/10.1079/ab.2025.0045
Mishra, P. (2023). Digital Entrepreneurship. 11-26. https://doi.org/10.4018/978-1-6684-5871-6.ch002
Motlagh, N. H., Zaidan, M. A., Lovén, L., Fung, P. L., Hänninen, T., Morabito, R., Nurmi, P., & Tarkoma, S. (2024). Digital Twins for Smart Spaces—Beyond IoT Analytics. *Ieee Internet of Things Journal*, *11*(1), 573-583. https://doi.org/10.1109/jiot.2023.3287032
Mweha, M. (2025). Digital Transformation and Strategic Resilience: A Framework for Sustainable Women Entrepreneurship in Zimbabwe's Post-Covid Economy. *International Journal of Research and Innovation in Social Science*, *IX*(XIV), 1269-1281. https://doi.org/10.47772/ijriss.2025.914mg0096
O'Donncha, F., Langbridge, A., Timms, A., Antonopoulos, A., Mygiakis, A., & Voulgari, E. (2025). Agentic AI for Ship Routing. https://doi.org/10.5194/egusphere-egu25-19197
Puppala, A. (2025). The Role of Digital Twins in AI-Driven Enterprise BI: Transforming Scenario Simulation and Strategic Planning. *European Journal of Computer Science and Information Technology*, *13*(44), 96-103. https://doi.org/10.37745/ejcsit.2013/vol13n4496103
Ramanamuni, S. (2025). The Role of Digital Twins in Supply Chain Optimization. *Interantional Journal of Scientific Research in Engineering and Management*, *09*(03), 1-6. https://doi.org/10.55041/ijsrem41779
Rana, R., & Bhambri, P. (2025). Harnessing Block Chain Digital Twins for Sustainable Business Operations. 413-446. https://doi.org/10.4018/979-8-3373-2018-2.ch013
Ravi, V., Jampani, S., Gudavalli, S., Goel, O., Jain, P. A., & Kumar, L. (2024). Role of Digital Twins in SAP and Cloud Based Manufacturing. *JQST*, *1*(4). https://doi.org/10.63345/jqst.v1i4.101
Satpathy, R. B., & Gavaskar, S. (2021). Utilisation of Digital Twin in Representation of a Physical Object, Process, or Service. *Technoarete Transactions on Internet of Things and Cloud Computing Research*, 1-5. https://doi.org/10.36647/0805011iotccr
Sinitsyn, S. N. (2024). Digital Twins as a Tool for Shaping the Business Environment of Modern Organizations. *Financial Analytics Science and Experience*, *17*(4), 454-471. https://doi.org/10.24891/fa.17.4.454
Srivastava, G., & Bag, S. (2025). Harnessing Digital Twin Technology To enhance Resilience in Humanitarian Supply Chains: An Empirical Study. *Benchmarking an International Journal*. https://doi.org/10.1108/bij-12-2024-1143
Szewczyk, P. (2021). Mangement of Blockchain Based Digital Assets in Industry and Services. *Scientific Papers of Silesian University of Technology Organization and Management Series*, *2021*(150), 267-277. https://doi.org/10.29119/1641-3466.2021.150.20
Telnov, Y., Kazakov, V. I., Danilov, A., & Fiodorov, I. (2024). Network Enterprise Architecture Based on Multiagent Technology. *Revista Gestão & Tecnologia*, *24*(Special), 01-15. https://doi.org/10.20397/2177-6652/2024.v24i00.2719
Timms, A., Langbridge, A., Antonopoulos, A., Mygiakis, A., Voulgari, E., & O'Donncha, F. (2025). Agentic AI for Digital Twin. *Proceedings of the Aaai Conference on Artificial Intelligence*, *39*(28), 29703-29705. https://doi.org/10.1609/aaai.v39i28.35373
Tonani, M., Arnaud, A., Tyberghein, L., Gaudel, Q., Gaspéri, J., Vera, J., Delaney, C., & Leclercq, F. (2025). European Digital Twin Ocean Platform: An Innovative Platform for Making Ocean Knowledge Readily Available. https://doi.org/10.5194/oos2025-1545
Vetrivel, S. C., Sowmiya, K. C., & Sabareeshwari, V. (2024). Digital Twins. 111-131. https://doi.org/10.4018/979-8-3693-3234-4.ch009
Xu, Y., He, P., & Hu, H. (2024). Vehicle Digital Dashboard Design and Simulation System Based on Digital Twin Technology. 43. https://doi.org/10.1117/12.3033317
Yan, M.-R., Hong, L.-Y., & Warren, K. (2021). Integrated Knowledge Visualization and the Enterprise Digital Twin System for Supporting Strategic Management Decision. *Management Decision*, *60*(4), 1095-1115. https://doi.org/10.1108/md-02-2021-0182