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The Digital Pivot: A Systematic Review of Digital Technology's Impact on Manufacturing and Future Research Agenda

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ABSTRACT

The manufacturing sector is undergoing a profound transformation driven by the pervasive integration of digital technologies (DTs), often termed "Industrial Digitalization." While previous literature has extensively focused on Industry 4.0, a comprehensive and nuanced understanding of Industrial Digitalization — encompassing its diverse technological enablers, organizational prerequisites, multi-faceted impacts, and inherent barriers — remains fragmented. This systematic literature review synthesizes 150 high-impact studies from 2018 to 2025 to develop a holistic conceptual framework that distinguishes Industrial Digitalization from its predecessors. We classify DTs into five core categories (AI/ML, IIoT, Digital Twin, Cloud/Edge Computing, and Big Data Analytics) and systematically analyze their impact mechanisms. Our key finding is the confirmation of DTs as a critical driver for enhancing Total Factor Productivity (TFP) in manufacturing, primarily through the mediation of data-driven decision-making, resource allocation optimization, and knowledge spillover. Furthermore, we identify critical barriers (e.g., organizational inertia, skill gaps, ethical concerns) and, most importantly, propose a five-point future research agenda, focusing on the need for a more nuanced conceptualization, the potential for DTs to evolve into General-Purpose Technologies, and the imperative to integrate ethical and sustainability principles into digitalization strategies. This review provides a robust theoretical foundation for researchers and actionable insights for practitioners and policymakers navigating the complex landscape of the digital manufacturing era.

INTRODUCTION

The global manufacturing landscape is at an inflection point, transitioning from the automation-centric paradigm of Industry 3.0 to a hyper-connected, data-driven ecosystem. This shift, broadly defined as Industrial Digitalization, involves the integration of advanced digital technologies (DTs) into all aspects of the manufacturing value chain, from product design and production to supply chain management and customer service. Unlike the narrower focus of "Industry 4.0," which often emphasizes Cyber-Physical Systems (CPS) and the Industrial Internet of Things (IIoT), Industrial Digitalization represents a broader,

socio-economic transformation, affecting not only technological systems but also organizational structures, business models, and labor markets [1].

The urgency of this transformation is reflected in the massive global investment. The market for digital transformation in manufacturing is projected to grow from \$440 billion in 2025 to \$847 billion by 2030, underscoring the strategic importance of this domain [2].

Despite the proliferation of research, a systematic synthesis that clearly outlines the mechanisms through which DTs exert their influence, particularly on core economic metrics like Total Factor Productivity (TFP), remains a gap. This review addresses this by:

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(1) Developing a comprehensive conceptual framework for Industrial Digitalization based on the influential work of Matt et al. [3], encompassing technological enablers, intangible enablers, barriers, and impacts.

(2) Systematically classifying the core DTs and their specific applications across the manufacturing value chain.

(3) Providing an in-depth analysis of the core impact mechanism, specifically the direct and indirect effects of DTs on TFP.

(4) Proposing a structured, five-point future research agenda for high-impact studies in the field.

1. Research Methodology

This review adopts a systematic literature review (SLR) approach to ensure rigor and replicability. The search strategy focused on high-quality, peer-reviewed articles indexed in SCI and SSCI databases (Web of Science, Scopus, ScienceDirect).

Search Terms: ("digital transformation" OR "digital technology" OR "Industry 4.0") AND ("manufacturing" OR "production") AND ("impact" OR "effect" OR "TFP" OR "productivity" OR "literature review"). **Timeframe:** 2018–2025, focusing on the most recent and impactful research. **Selection Criteria:** The initial search yielded over 1,500 results. After filtering by title, abstract, and full-text screening for relevance, conceptual contribution, and methodological rigor, a final corpus of 150 core articles was selected for in-depth synthesis.

2. The Conceptual Framework of Industrial Digitalization

To move beyond simple technology descriptions, we adopt and refine a multi-layered conceptual framework [3] that organizes the literature into four non-mutually exclusive categories:

Category	Description	Key Components & Examples
Technological Enablers	The core digital technologies that make the transformation possible.	AI/ML, IIoT, Digital Twin, Cloud/Edge Computing, Big Data Analytics.
Intangible Enablers	Organizational, managerial, and human factors required for	Leadership, Organizational Culture, Digital Skills, Change

Category	Description	Key Components & Examples
	successful DT adoption.	Management, Inter-firm Collaboration.
Barriers	Obstacles hindering the adoption and implementation of DTs.	High initial investment, Data security risks, Organizational inertia, Skill gaps, Lack of clear ROI.
Impacts	The resulting changes across economic, organizational, and societal dimensions.	TFP enhancement, Business Model Innovation (Servitization), Sustainability, Labor Market Restructuring.

Table.1. The Conceptual Framework of Industrial Digitalization

This framework serves as the structural backbone of our review, ensuring a holistic analysis that considers both the "what" (technology) and the "how" (mechanisms, enablers, barriers) of industrial digitalization.

3. Technological Enablers and Applications

The foundation of Industrial Digitalization rests on a convergence of powerful DTs. We categorize the most critical technologies and their primary applications in the manufacturing value chain (Design, Production, Supply Chain, Service):

Core Digital Technology	Key Application in Manufacturing	Value Proposition
Artificial Intelligence (AI) & Machine Learning (ML)	Predictive maintenance, Real-time quality control, Production scheduling optimization, Generative design.	Reduces downtime, minimizes defects, optimizes resource utilization.
Industrial Internet of Things (IIoT) & Sensors	Real-time asset tracking, Condition monitoring, Remote diagnostics, Data collection from shop floor.	Provides the foundational data layer for all other DTs; enhances transparency and responsiveness.
Digital Twin (DT)	Process simulation, Virtual commissioning, Product lifecycle	Enables risk-free optimization and continuous process improvement across

Core Technology	Digital Technology	Key Application in Manufacturing	Value Proposition
Cloud & Edge Computing		management, 'What-if' scenario testing.	the product and process lifecycles [4].
		Scalable data storage and processing, Distributed manufacturing control, Real-time analytics at the source.	Offers flexible, cost-effective computing power and low-latency processing for critical operations.
		Demand forecasting, Root cause analysis of defects, Personalized product configuration, Supply chain risk prediction.	Translates raw data into actionable insights, driving smarter operational and strategic decisions.
Big Data Analytics (BDA)			

Table.2.Technological Enablers and Applications

The most significant trend is the synergistic integration of these technologies, particularly the combination of AI/ML with Digital Twins and IIoT [5]. This integration creates a closed-loop system where IIoT collects data, AI/ML analyzes and predicts, and the Digital Twin simulates and validates changes before implementation in the physical world.

4.Core Impact Mechanisms: TFP and Beyond

The ultimate measure of digital technology's economic value in manufacturing is its impact on Total Factor Productivity (TFP), which captures efficiency gains not attributable to changes in labor or capital inputs. Recent empirical studies consistently confirm that DTs significantly promote TFP in manufacturing enterprises [6, 7]. We identify three primary mechanisms:

4.1.The TFP Enhancement Mechanism

The impact of DTs on TFP is not direct but mediated through the creation and exploitation of data-driven capabilities. This process can be conceptualized as a flow:

(1) Enablers to Data: Core DTs (AI/ML, DT, IIoT) transform physical processes into digital data streams, enabling Real-time Data Analysis and the Digitalization of the Physical World.

(2) Data to Decision: The analyzed data feeds into the central process of Data-Driven Decision Making (DDDM). DDDM is the critical pivot point, translating technological input into organizational output.

(3) Decision to Optimization: DDDM simultaneously triggers three core optimization pathways:

Resource Allocation Optimization: Better matching of inputs (materials, energy, labor) to outputs, reducing waste and idle capacity.

Production Process Optimization: Real-time adjustments to machine parameters, scheduling, and flow, leading to higher throughput and quality.

Knowledge Spillover & Innovation: Data sharing and collaborative platforms foster organizational learning and accelerate product/process innovation.

(4) Optimization to TFP: These three optimization pathways converge to drive significant TFP Enhancement, representing a fundamental shift in the production function.

4.2.Beyond TFP: Business Model and Sustainability

Beyond efficiency, DTs drive two other transformative impacts:

Business Model Transformation (Servitization): DTs enable manufacturers to shift from selling products to selling outcomes or services (Servitization). For example, a machine manufacturer can use IIoT data and AI to offer "uptime-as-a-service" or "performance-as-a-service," creating new revenue streams and deepening customer relationships [8]. This transformation also contributes to overall Enterprise Competitiveness.

Sustainability and Resilience: Digitalization enables Green Manufacturing by optimizing energy consumption, reducing material waste through precise process control (DTs), and improving supply chain transparency to track carbon footprints. The integration of ethical and sustainability principles is increasingly recognized as a non-negotiable impact dimension [3].

5.Barriers and Intangible Enablers

The path to Industrial Digitalization is fraught with challenges, which are often non-technical.

5.1. Critical Barriers

Barrier Category	Description	Implication for Adoption
Financial	High initial investment costs, long payback periods, and difficulty in quantifying the Return on Investment (ROI) for intangible assets (e.g., data infrastructure).	Disproportionately affect Small and Medium Enterprises (SMEs) [9].
Organizational	Organizational inertia, resistance to change from employees, lack of cross-functional collaboration, and siloed data systems.	Requires strong change management and top-down commitment.
Human Capital	Severe skill gaps in data science, cybersecurity, and operational technology (OT)/IT integration; difficulty in attracting and retaining digital talent.	Hinders the effective deployment and maintenance of advanced DTs.
Data & Security	Data privacy concerns, cybersecurity threats, and the complexity of integrating heterogeneous data sources across the value chain.	Requires robust data governance and security protocols.

Table.3.Critical Barriers

5.2. Intangible Enablers

Successful digitalization hinges on the presence of Intangible Enablers—the soft infrastructure of the organization:

Digital Leadership: Visionary leadership that champions the digital strategy and allocates necessary resources.

Agile Organizational Culture: A culture that embraces experimentation, continuous learning, and tolerance for

failure.

Digital Literacy: Investment in upskilling and reskilling the existing workforce to bridge the skill gap and foster acceptance.

6.Future Research Agenda

Based on our synthesis and the identification of existing research gaps, we propose a five-point agenda for future high-impact research to guide the next generation of studies in this critical domain:

Nuanced Conceptualization and Measurement: Future research must move beyond treating "Industrial Digitalization" as a monolithic concept. We need validated, multi-dimensional scales to measure the intensity and scope of DT adoption across different manufacturing sub-sectors and firm sizes. This will allow for more precise causal inference regarding its impacts.

DTs as General-Purpose Technologies (GPTs): A critical theoretical question is whether technologies like AI or Digital Twins will achieve the status of GPTs, fundamentally transforming entire economies (similar to electricity or the computer). Future studies should empirically test the spillover effects and long-term macro-economic impacts of these technologies beyond the firm level.

Contingency Effects and Heterogeneity: The impact of DTs is highly heterogeneous. Research should focus on contingency approaches, examining how the effects of digitalization vary based on: (a) firm-level factors (e.g., size, ownership, existing technological base); (b) industry-level factors (e.g., discrete vs. process manufacturing); and (c) national/regional institutional contexts (e.g., policy support, labor market regulations) [10].

Inter-firm Collaboration and Ecosystems: As manufacturing becomes increasingly networked, future research must develop and test models for accurate inter-firm collaboration among digital manufacturers. This includes studying the governance, trust mechanisms, and data-sharing protocols required for effective digital supply chain ecosystems.

Integrating Ethics, Sustainability, and Resilience: The long-term success of digitalization depends on its compatibility with societal goals. Research is urgently needed on: (a) the ethical implications of AI-driven decision-making in production; (b) the trade-offs and synergies between digitalization and environmental sustainability (Green Manufacturing); and (c) how DTs can

enhance supply chain resilience against global shocks.

Conclusion

Industrial Digitalization is not merely a technological upgrade but a fundamental re-engineering of the manufacturing value proposition. This systematic review has provided a structured conceptual framework, detailed the core technological enablers, and, most critically, elucidated the mediated mechanism through which DTs drive TFP enhancement in the sector. By confirming the central role of data-driven decision-making and highlighting the non-technical barriers (organizational inertia, skill gaps), this review offers a comprehensive map of the current state of knowledge. The proposed five-point research agenda serves as a call to action for the academic community to address the most pressing, high-impact questions that will define the future of digital manufacturing.

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