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Management 4.0 in Smart Manufacturing: A Systematic Review, Gap Analysis, and Future Roadmap

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Abstract

Management 4.0, driven by digital transformation and Industry 4.0 technologies, is reshaping organizational structures, managerial paradigms, and value creation mechanisms in smart manufacturing systems. Enabled by the convergence of artificial intelligence, cyber-physical systems, advanced analytics, and interconnected digital infrastructures, manufacturing organizations are increasingly transitioning toward adaptive, autonomous, and data-driven management models that transform decision-making, coordination, and operational governance.

Despite growing scholarly attention, the Management 4.0 domain remains fragmented and under-theorized. Existing literature exhibits limited conceptual integration, inconsistent empirical validation, and a lack of scalable implementation frameworks. In particular, the socio-technical complexity of integrating intelligent systems with human decision-making across organizational transformation, workforce evolution, governance redesign, and sustainability (including ESG integration) remains insufficiently addressed.

To address these gaps, this study conducts a systematic review of more than 200 peer-reviewed publications (2011-2026), supported by structured gap analysis. Grounded in socio-technical systems theory and the dynamic capabilities perspective, it reframes Management 4.0 as an integrated organizational transformation paradigm rather than a set of isolated digital initiatives.

The synthesis develops a consolidated conceptual framework structured into four interdependent capability domains: technological infrastructure, organizational architecture, managerial and leadership capabilities, and governance systems. Three critical gaps are identified: absence of a unified theoretical foundation, limited empirical validation of transformation pathways, and insufficient understanding of human-AI socio-technical integration in smart manufacturing contexts.

Finally, a ten-step implementation roadmap is proposed, encompassing digital maturity assessment, strategic alignment, digital architecture design, capability development, process reengineering, governance and ethics, innovation and risk management, customer-centric transformation, performance measurement, and knowledge management integration.

Keywords: management 4.0, smart manufacturing, industry 4.0, digital transformation, artificial intelligence, organizational transformation.

1. INTRODUCTION

Manufacturing organizations increasingly operate within volatile, uncertain, complex, and ambiguous (VUCA) environments shaped by rapid technological change, deepening global interdependencies, evolving customer expectations, and intensifying environmental disruptions. In this

context, competitive advantage derives less from scale and efficiency and more from the ability to sense change, respond rapidly, and innovate continuously. Accordingly, sectors such as automotive, logistics, energy, and healthcare are shifting from reactive, experience-based management toward predictive, data-driven decision-making. Simultaneously, growing exposure of global supply chains to geopolitical tensions and climate-related risks reinforces the need for real-time visibility, resilience, and strategic agility (Dossou et al., 2022; McDermott et al., 2023; Gomaa, 2024; Duarte & Dong, 2025; Fahima et al., 2025; Jindia & Chawla, 2026) [54,147,78,55,60,113].

In response, Management 4.0 has emerged as a socio-technical paradigm integrating advanced digital technologies with human-centric leadership and adaptive organizational capabilities. Beyond technology adoption, it reconfigures the alignment of strategy, structure, processes, and culture in data-intensive environments. It incorporates managerial cognition, governance architectures, and organizational learning to enhance resilience, foster innovation, and sustain competitive advantage. By linking technological infrastructures with human intelligence and leadership practices, Management 4.0 provides an integrative logic for navigating complexity and leveraging emerging opportunities (Yılmaz Gezgin & Arıcıoğlu, 2025) [236].

Existing research has examined Industry 4.0 from multiple perspectives. Dobrowolska and Knop (2020) emphasize shifts in competition and sustainability [52], while Sulich and Zema (2025) highlight evolving management paradigms [209]. Mohelska and Sokolova (2018) show how digitalization reshapes organizational culture and capabilities [154], and Saucedo-Martínez et al. (2018) stress the importance of information management for managerial effectiveness [194]. Shamim et al. (2016) further identify emerging managerial competencies in technology-intensive environments [200].

Despite these contributions, the literature remains fragmented and insufficiently integrative. Prior studies typically examine technological, organizational, or human dimensions in isolation, offering limited insight into their interdependencies. Consequently, comprehensive frameworks linking Industry 4.0 technologies with management transformation and cross-domain integration in manufacturing contexts remain underdeveloped (Moeuf et al., 2020; McDermott et al., 2022) [151,146].

This study addresses these limitations by providing an integrated literature review, systematic gap analysis, and a multi-level conceptual roadmap for Management 4.0 in smart manufacturing organizations. By synthesizing dispersed research and connecting technological, organizational, and human dimensions, it positions Management 4.0 as an orchestrating capability for adaptive and resilient manufacturing systems.

1.1 From Traditional Management to Smart Management 4.0

Traditional management systems are hierarchical, control-oriented, and efficiency-driven. Decision-making is largely retrospective, based on historical data, standardized procedures, and managerial intuition. Processes are linear and rigid, while functional silos constrain collaboration and knowledge sharing. Performance measurement relies on lagging indicators, risk management is reactive, and innovation is incremental. These characteristics prioritize stability over adaptability (Wren & Bedeian, 2023) [230].

In contrast, Smart Management 4.0 reflects a shift toward adaptive, intelligent, and data-driven organizations. Decision-making becomes predictive and real-time, enabled by advanced analytics, artificial intelligence, and integrated data ecosystems. Processes evolve into flexible, automated, and self-optimizing systems, while the workforce becomes knowledge-intensive, collaborative, and continuously learning through digital platforms (Hrinchenko, 2021) [101].

1.2 Applications of Industry 4.0 Across Manufacturing Organizational Domains

Industry 4.0 is driving a systemic reconfiguration of manufacturing organizations by redefining how value is created, coordinated, and delivered across domains, including operations, strategy, human capital, customer engagement, finance, and sustainability. Enabling technologies—such as IoT, artificial intelligence, robotics, augmented reality, big data analytics, cloud computing, and cyber-physical systems—support real-time sensing, predictive analytics, adaptive automation, and

decentralized decision-making (Moeuf et al., 2018; Javaid & Haleem, 2021; Abu-Lail et al., 2025; Ali et al., 2026; Bello et al., 2026) [152,110,1,8,25].

These technologies function as an integrated ecosystem rather than isolated tools. Continuous data flows across domains enable alignment between operational execution and strategic intent while supporting rapid responses to environmental volatility. Consequently, competitive advantage increasingly depends on the orchestration of technological, human, and organizational capabilities (Felsberger & Reiner, 2020; Fatorachian & Kazemi, 2021; Barenji et al., 2024; Bai et al., 2026) [64,63,24,23].

Table 1 and Figure 1 illustrate Industry 4.0 applications across domains, highlighting functional capabilities, strategic outcomes, and the integrative role of Management 4.0. For example:

- 1) Operations and Manufacturing Cluster: Manufacturing 4.0 and Operations 4.0 enable adaptive production, predictive maintenance, and real-time optimization. SCM 4.0 extends these capabilities across networks, while Lean 4.0, Kaizen 4.0, and Six Sigma/LSS 4.0 embed continuous improvement within data-driven systems (Buer et al., 2018; Adu-Amankwa et al., 2019; Antony et al., 2021; Achouch et al., 2022; Aljohani, 2023; Alonge et al., 2023; Antony et al., 2023a; Gomaa, 2025a, 2025b, 2025c) [32,5,16,4,11,12,15,79,80,81].
- 2) Quality and Risk Management Cluster: Quality 4.0 integrates digital twins and AI-enabled analytics, while FMEA 4.0 and Risk and Compliance 4.0 support predictive and real-time risk management (Albers et al., 2016; Ammar et al., 2021; Broday, 2022; Ammar et al., 2022; Ali & Johl, 2023; Antony et al., 2023b; Antony et al., 2024; Gomaa, 2025d, 2025e, 2025f) [7,13,31,14,8,17,18,82,83,84].
- 3) Strategy and Business Management Cluster: PM 4.0 and BM 4.0 enable real-time performance monitoring and business model innovation, while Strategy 4.0 ensures alignment with long-term objectives (Cakmakci, 2019; Cerezo-Narváez et al., 2021; Somarathna et al., 2026; Nagy et al., 2026) [34,37,204,158].
- 4) Human Capital and Collaboration Cluster: HR 4.0 and Knowledge 4.0 enhance talent development, collaboration, and collective intelligence (Bogoviz, 2018; Ansari, 2019; Jabeen et al., 2025; Jhavar et al., 2026; Azuwandri, 2026; Grillo et al., 2026; Haverila et al., 2026; Bello et al., 2026) [29,15,105,112,22,87,96,25].
- 5) Customer and Market Cluster: Customer Experience 4.0 and Marketing 4.0 enable personalization and responsiveness, while Innovation 4.0 accelerates development cycles (Sun et al., 2021; Santamaria-Ruiz et al., 2025; Chen, 2026; Vishnoi et al., 2026; Grover et al., 2026) [210,191,40,224,88].
- 6) Finance, Analytics, Security, and Sustainability Cluster: Finance 4.0, Analytics 4.0, Security 4.0, and Sustainability 4.0 enhance decision-making, system integrity, and ESG alignment (Lutsiv et al., 2023; Verma et al., 2026; Thanasas et al., 2026; Chitongo, 2026; Santos et al., 2026) [137,221,215,45,193].
- 7) Cross-Cluster Integration: Value emerges through systemic integration and continuous learning loops (Gomaa, 2025h; Handoyo & Sueb, 2026; Piispanen & Hentunen, 2026) [86,95,178].
- 8) Management 4.0 as the Orchestrator: Management 4.0 aligns technological systems, human capabilities, and strategic objectives, enabling coordinated and adaptive organizational behavior (Almannai, 2026; Jhavar & Sharma, 2026; Arcia-Hernández et al., 2026) [12,112,20].

1.3 Smart Organizations and the Role of Management 4.0

Management 4.0 enhances performance by leveraging technologies such as AI, VR, IoT, robotics, and additive manufacturing, which augment human capabilities and enable real-time, data-driven decisions (Haleem et al., 2023) [94]. It also facilitates the integration of software, hardware, and human expertise, enabling real-time information flows and coordinated operations (Lee et al., 2019; Acerbi et al., 2019; Javaid & Haleem, 2019) [130,2,109].

Rooted in Industry 4.0, Management 4.0 reflects the convergence of technological and managerial transformation across sectors (Hecklau et al., 2016; Mastos et al., 2021; Raptis et al., 2019) [97,143,183]. Its implementation requires advanced infrastructure, robust data integration, and analytics capabilities. Workforce roles evolve toward multi-skilled professionals, while managers act as facilitators in interconnected systems. Technologies such as blockchain enhance transparency and traceability (Zhou et al., 2015; Romanovs et al., 2019; Mehta et al., 2021; Robert et al., 2022; Esmailian et al., 2020) [242,185,148,184,59].

1.4 Research Gaps and Implementation Challenges

Despite growing interest, the Management 4.0 literature remains fragmented and lacks theoretical integration. Key dimensions—including socio-technical alignment, governance, ethics, organizational redesign, workforce transformation, and leadership—remain underexplored (Zheng et al., 2018; Zong & Guan, 2025) [241,243].

Implementation is constrained by technological complexity, resistance to change, skills shortages, fragmented governance, and limited integration of sustainability practices. Additional gaps persist in understanding cross-domain interactions, enterprise data governance, and innovation-risk alignment.

Addressing these challenges requires an integrated perspective aligning technological, organizational, and human dimensions to enable adaptive and resilient performance.

1.5 Study Objectives and Contributions

This study provides a comprehensive literature review, gap analysis, and conceptual roadmap for Management 4.0 in smart manufacturing organizations, integrating fragmented research into a coherent framework linking technological transformation with managerial innovation and organizational design. The study addresses the following research questions:

- 1) Foundations & Management Systems:
 - RQ1: How does Management 4.0 transform management systems and governance?
 - RQ2: Which technological, organizational, and human factors are critical for adoption?
 - RQ3: How does Management 4.0 enhance workforce performance, collaboration, and governance?
- 2) Innovation & Competitive Advantage:
 - RQ4: How does Management 4.0 influence operational and strategic outcomes?
 - RQ5: How does it promote organizational learning, innovation, and sustainable competitive advantage?
- 3) Implementation, Sustainability & Resilience:
 - RQ6: What are the key enablers and barriers to implementation?
 - RQ7: How do cross-domain interactions enhance resilience and adaptability?

By addressing these questions, the study develops a multi-level conceptual framework and a ten-step roadmap. It contributes by synthesizing literature, clarifying constructs, and providing actionable managerial guidance.

The remainder of the paper is structured as follows: Section 2 presents the literature review; Section 3 provides the gap analysis; Section 4 introduces the framework and roadmap; and Section 5 concludes with implications and future research directions.

Table 1. Industry 4.0 Applications Across Organizational Domains.

#	Cluster	Domains	Core Capabilities	Impact
1	Operations & Manufacturing	Manufacturing 4.0, Operations 4.0, SCM 4.0, Maintenance 4.0, Lean/Kaizen 4.0, Six Sigma/LSS 4.0	Adaptive production, predictive maintenance, process optimization	Higher efficiency, agility, reliability, and reduced downtime

2	Quality & Risk Management	Quality 4.0, FMEA 4.0, Risk & Compliance 4.0	Real-time quality control, predictive risk, compliance monitoring	Resilience, risk reduction, and regulatory compliance
3	Strategy & Business Management	Performance Mgmt 4.0, Business Model 4.0, Business Mgmt 4.0, Strategy 4.0	KPI tracking, scenario planning, resource alignment	Strategic agility, better decisions
4	Human Capital & Collaboration	HR 4.0, Collaboration & Knowledge 4.0	Talent development, knowledge sharing	Skilled, adaptable workforce; faster learning
5	Customer & Market	Customer Experience 4.0, Marketing 4.0, Innovation 4.0	Personalization, predictive insights, rapid innovation	Customer satisfaction, responsiveness, faster time-to-market
6	Finance, Analytics, Security & Sustainability	Finance 4.0, Analytics & Decision 4.0, Security & Cyber-Defense 4.0, Sustainability 4.0	Financial intelligence, enterprise analytics, cyber defense, ESG integration	Secure, compliant, sustainable, data-driven operations
7	Management 4.0 (Integrator)	Cross-cluster orchestration	Integration, real-time monitoring, coordination	System-wide alignment, continuous improvement, competitiveness

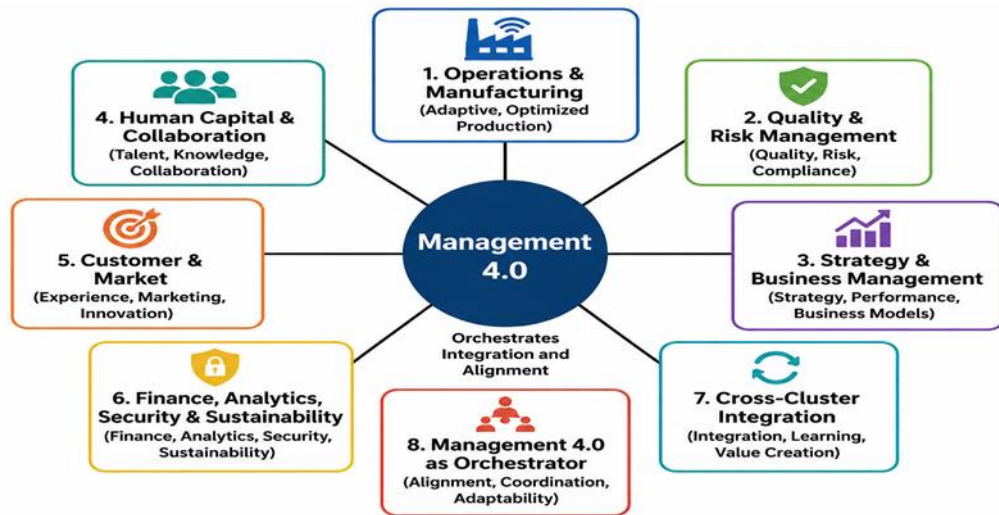


Figure 1. Industry 4.0 Applications Across Organizational Domains

2. LITERATURE REVIEW

This literature review examines peer-reviewed studies published between 2011 and 2026 across Scopus, Web of Science, and ScienceDirect, focusing on Management 4.0, smart organizations, and Industry 4.0 technologies. The objective is to synthesize existing knowledge, identify critical research gaps, and establish a conceptual foundation for future research and implementation. The review integrates interdisciplinary perspectives spanning digital transformation, organizational agility, artificial intelligence, advanced analytics, managerial practices, organizational design, and governance mechanisms.

This study adopts a PRISMA 2020-aligned systematic literature review to ensure methodological

transparency, reproducibility, and analytical rigor (Page et al., 2021) [172].

- 1) **Data Sources and Search Strategy:** Literature was retrieved from Scopus, Web of Science, and ScienceDirect, selected for their extensive coverage of peer-reviewed research in management science, industrial engineering, operations management, information systems, and digital transformation. This multi-source strategy reduces indexing bias and strengthens evidence reliability. A reproducible search strategy was developed a priori using Boolean operators (AND/OR), integrating Industry 4.0 and Management 4.0 with enabling technologies such as cyber-physical systems, industrial internet of things, artificial intelligence, machine learning, and advanced analytics. A consistent semantic structure was applied across databases. Only English-language peer-reviewed journal articles and conference papers published between 2011 and 2026 were included.
- 2) **Eligibility Criteria:** Inclusion criteria comprised studies addressing technological, managerial, organizational, or strategic dimensions of Industry 4.0, smart manufacturing, smart organizations, or Management 4.0. Exclusion criteria included duplicate records, non-peer-reviewed sources, methodologically weak studies, and off-scope contributions. This ensured conceptual clarity and analytical consistency in an interdisciplinary and rapidly evolving research domain.
- 3) **Screening Process and PRISMA Workflow:** Following PRISMA 2020 guidelines, 294 records were identified (Scopus: 118; Web of Science: 92; ScienceDirect: 84). After removing 61 duplicates, 233 records were screened. Title and abstract screening excluded 88 studies, leaving 145 full-text articles for eligibility assessment. Following full-text review, 43 studies were excluded due to methodological or conceptual limitations. Ultimately, 102 studies formed the core synthesis dataset. To enhance coverage and mitigate publication and indexing bias, approximately 100 additional studies were included through backward and forward citation tracking, resulting in a final corpus exceeding 200 publications (2011-2026). The process is illustrated in Figure 1 (PRISMA flow diagram), ensuring transparency and reproducibility.
- 4) **Quality Assessment:** A structured appraisal was conducted to evaluate methodological transparency, research rigor, analytical depth, theoretical contribution, and relevance to Industry 4.0 and Management 4.0. Only studies meeting predefined quality thresholds were retained, ensuring robustness and validity of the synthesis.
- 5) **Data Synthesis:** Thematic synthesis was conducted through iterative coding, axial categorization, and constant comparison. This enabled integration of interdisciplinary evidence across digital transformation, cyber-physical systems, artificial intelligence, machine learning, advanced analytics, organizational design, managerial decision-making, and governance mechanisms. The synthesis indicates a dominant emphasis on technological enablers, while organizational, behavioral, and governance dimensions remain comparatively underdeveloped, revealing a structural imbalance in the literature.
- 6) **Methodological Positioning:** The study establishes a PRISMA protocol tailored to socio-technical transformation research, addressing a key limitation in prior literature—descriptive aggregation without sufficient theoretical consolidation. This enhances reproducibility while aligning the review with socio-technical systems theory and dynamic capabilities perspectives.

Finally, the literature is organized into four interdependent streams: (i) digital transformation as a foundational enabler of Management 4.0, (ii) Industry 4.0 technologies as operational enablers of smart manufacturing, (iii) Management 4.0 as a socio-technical transformation paradigm integrating intelligent decision-making, adaptive governance, and organizational agility, and (iv) cross-cutting challenges including socio-technical integration, human-AI collaboration, ethical governance, and decision-support limitations. Collectively, these streams expose a persistent imbalance between technological advancement and organizational-governance maturity, thereby providing a direct conceptual basis for the subsequent gap analysis and future roadmap.

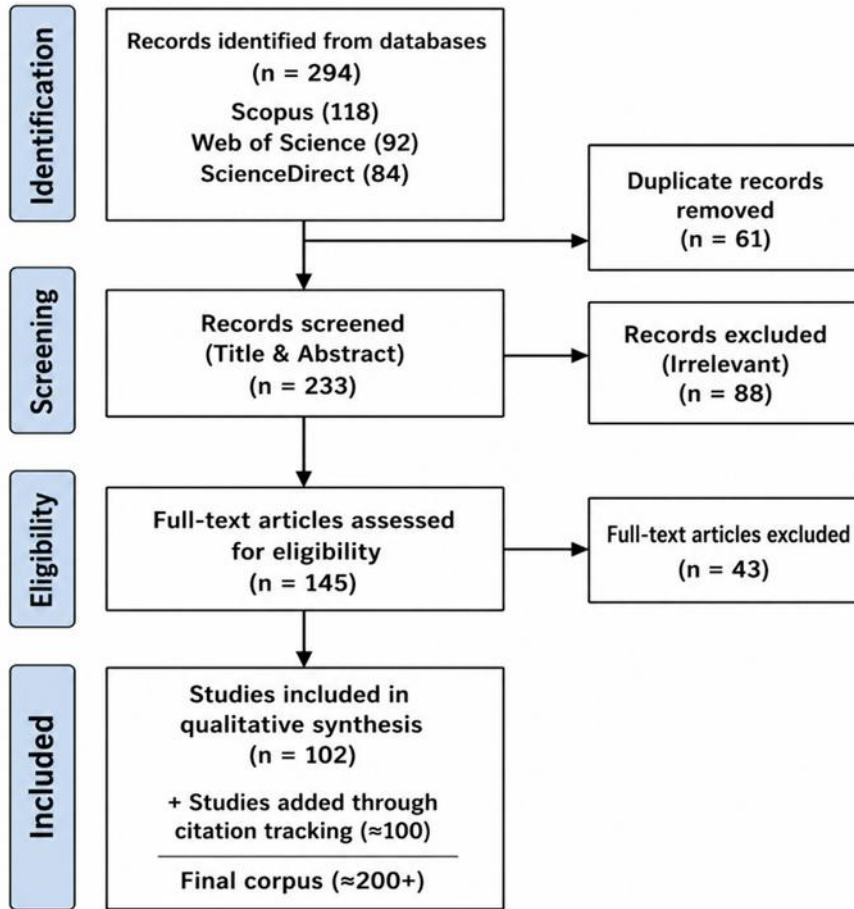


Figure 2. PRISMA-2020 flow diagram for the data selection process and systematic reviews

2.1. Review of Digital Transformation as a Foundation for Management 4.0

Digital transformation has emerged as a critical driver of competitiveness, operational efficiency, and sustainable growth, particularly in smart manufacturing. It reshapes how knowledge is generated, shared, and applied, fundamentally transforming workflows, decision-making, and collaboration. Traditional hierarchical management models and static career pathways are increasingly inadequate; managers and professionals must develop digital literacy, analytical and strategic thinking, adaptability, and ethical decision-making (Omol et al., 2024; da Silva et al., 2025; Makori & Omangi, 2026; Adakpo, 2026) [170,46,141,4].

Management 4.0 emphasizes human-centered leadership, data-driven decision-making, and organizational agility within smart manufacturing ecosystems characterized by cyber-physical systems, IoT, and AI convergence. Digital transformation entails reconfiguring business models, operational strategies, and competitive positioning, integrating digital solutions (DSs) across processes to enable intelligent, adaptive systems that support real-time decision-making, predictive maintenance, and resource optimization (Thekkoote, 2022; Fernandez-Vidal et al., 2022; Shahadat et al., 2023) [216,66,199].

The progression toward digital maturity typically unfolds through digitization, digitalization, and full digital transformation (Loebbecke & Picot, 2015; Parviainen et al., 2017) [134,174]. Digitization converts analog data into digital formats, enabling automation and real-time monitoring (Verhoef et al., 2021) [220]. Digitalization leverages IT infrastructure to streamline workflows and enhance stakeholder interactions (Pagani & Pardo, 2017) [173]. Full digital transformation reshapes business

models, governance structures, supply chains, and organizational culture, supporting continuous innovation, data-driven decision-making, and strategic responsiveness (Pagani & Pardo, 2017; Eliseo et al., 2026) [173,57].

Digital solutions enhance decision-making, operational efficiency, and adaptability. In manufacturing, these systems align production with customer requirements, ensure regulatory compliance, and improve supply chain transparency (Szedmák, 2025; Vallurupalli & Bose, 2018) [213,219]. Automation allows employees to focus on innovation, product development, and quality improvement, contributing to cost reduction and resource optimization (Suri et al., 2017; Santos et al., 2021) [211,192].

Business analysis and agile methodologies support digital transformation. Business analysis ensures alignment between DSs and organizational objectives, reducing risks associated with technology adoption (Adakpo, 2026) [4]. Agile approaches like Scrum and Kanban enhance flexibility through iterative development, continuous feedback, and cross-functional collaboration (Dingsøyr et al., 2019; Serrador & Pinto, 2015) [51,202].

Human capital transformation underpins successful digital adoption. Advances in ICT and AI shape education and professional development, equipping managers with Industry 4.0 competencies (Tashtoush et al., 2023; Kelly et al., 2023) [214,121]. Organizational culture and leadership play decisive roles, as firms promoting learning, collaboration, and innovation are more successful in digital initiatives (Westerman et al., 2014) [229]. External enablers, such as telecommunications and fintech, enhance connectivity, data exchange, and financial agility, particularly for SMEs (Arner et al., 2022) [21].

Digital transformation also creates opportunities for SMEs to scale operations, enter international markets, and adopt innovative business models (Stallkamp & Schotter, 2019; North & Lorenzo, 2020) [207,165]. Despite prior studies on SME digital adoption and internationalization (Szabó, 2024) [212], their intersection within smart manufacturing remains underexplored, highlighting gaps in understanding Management 4.0 adoption and SME competitiveness (Guo et al., 2023; Fodor et al., 2026) [92,69].

Data-driven decision-making is a central pillar of Management 4.0, improving decision quality, responsiveness, and performance (McAfee & Brynjolfsson, 2012; Provost & Fawcett, 2013) [144,180]. Tools like RPA and advanced analytics optimize processes, enhance predictive maintenance, and improve product quality (Davenport & Ronanki, 2018; Wedel & Kannan, 2016) [47,228], though challenges persist in data quality, analytical capabilities, and governance.

Despite its benefits, digital transformation faces challenges including legacy systems, skills shortages, resistance to change, cybersecurity risks, infrastructure limitations, and misalignment with strategy (Westerman et al., 2014; Bharadwaj et al., 2013) [229,27]. A holistic approach integrating technology, culture, leadership, workforce development, and strategic alignment is essential to realize Management 4.0 in smart manufacturing fully.

2.2. Review of Industry 4.0 Applications in Smart Manufacturing toward Management 4.0

Industry 4.0 marks a transformative shift in manufacturing, from isolated automation to fully integrated cyber-physical production systems, combining digital technologies, physical processes, and managerial decision-making (Xu et al., 2018; Chen et al., 2023; Kar & Rai, 2025) [232,41,117]. These systems underpin Management 4.0, enabling data-driven decisions, real-time coordination, human-machine collaboration, and sustainability (Makris et al., 2019; Machado et al., 2020; Elhabashy et al., 2026) [142,138,56].

For SMEs, Industry 4.0 facilitates the shift from reactive, resource-limited operations to agile, responsive, and data-informed ecosystems, enhancing efficiency, competitiveness, and environmental performance (Fatorachian & Kazemi, 2018; Schroeder et al., 2019; Jovanovski et al., 2019; Samper et al., 2022) [62,197,114,190]. Scalable technologies allow SMEs to implement circular economy approaches, reduce energy consumption, and optimize resources despite constraints (Nascimento et al.,

2016; Ingaldi & Ulewicz, 2020; Ghobakhloo, 2020; Samper et al., 2022) [160,103,76,190].

Smart manufacturing in SMEs leverages IoT, AI, big data, cloud computing, machine learning, and additive manufacturing for real-time human-machine interactions (Chen et al., 2017; Longo et al., 2017; Morrar et al., 2017; Castelo-Branco et al., 2019; Frank et al., 2019) [39,135,156,35,71]. IoT networks enable predictive maintenance, production monitoring, and quality tracking, while AI and machine learning allow autonomous decision-making, adaptive scheduling, and demand forecasting (Zhang & Chen, 2020; Moosavi et al., 2021; Langmann & Rojas-Peña, 2016; Sony et al., 2021; Kayikci et al., 2022; Lee, 2023; Guo et al., 2023; Xu & Pan, 2024; Gomaa, 2025g) [238,155,127,206,119,129,92,233,85]. Big data analytics transforms operational data into actionable insights, and cloud computing offers cost-effective, scalable infrastructure (Leng et al., 2020; Novák et al., 2020; Saif-Ur-Rehman et al., 2024) [131,167,188].

Technologies like additive manufacturing, AR, collaborative robots, autonomous mobile systems, and digital twins enhance flexibility, customization, safety, and operational efficiency (Cheung et al., 2021; Franciosi et al., 2018; Jasiulewicz-Kaczmarek & Gola, 2019; Nardo et al., 2021; Pinciroli et al., 2023; Samadhiya et al., 2024) [43,70,108,159,179,189].

Effective implementation of Management 4.0 depends on horizontal, vertical, and end-to-end integration (Wang et al., 2016) [227]. Horizontal integration facilitates collaboration and co-innovation across suppliers, departments, and business partners, enhancing knowledge sharing and joint value creation (Foidl & Felderer, 2015; Pérez-Lara et al., 2020) [69,176]. Vertical integration connects shop-floor operations with enterprise management systems, improving transparency, coordination, and responsiveness across organizational levels (Pérez-Lara et al., 2020; Vaidya et al., 2018) [176,218]. End-to-end integration extends across the entire value chain, supporting traceability, predictive maintenance, and adaptive scheduling, thereby increasing operational efficiency, agility, and resilience throughout processes and systems (Stock & Seliger, 2016; Jayashree et al., 2021; Li & Lau, 2017; Sony & Naik, 2019) [208,111,132,205]. Together, these integration mechanisms create a connected, intelligent, and adaptive Management 4.0 ecosystem, establishing a foundation for sustainable competitiveness and effective digital transformation in smart manufacturing environments (Chauhan et al. 2022; Chavez et al., 2022) [38,39].

Operations Management 4.0 (OM 4.0) integrates IoT, AI, CPS, digital twins, and cloud computing for real-time monitoring, predictive analytics, and autonomous decision-making (Caiado et al., 2021; Helo & Hao, 2022; Dias et al., 2022) [33,99,49]. Maintenance, reliability, and emerging technologies such as 5G, edge AI, robotics, and blockchain strengthen operational resilience and cost efficiency (Cachada et al., 2018; Lee et al., 2020; Zhang et al., 2019; Kuo et al., 2017; Metso & Thenent, 2020; Giliyana et al., 2024; Rai et al., 2024; Jasiulewicz-Kaczmarek, 2024) [33,128,239,126,149,77,182,107].

Management 4.0 principles extend to supply chain, quality, safety, and operational excellence, integrating AI, IoT, CPS, blockchain, and cloud/edge computing for resilient, adaptive, and transparent systems (Tjahjono et al., 2017; Pasi et al., 2020; Frazzon et al., 2019; Helo & Hao, 2022; Wang et al., 2023; Shadravan & Parsaei, 2023; Saif-Ur-Rehman et al., 2024; Hofmann et al., 2019) [217,175,72,99,226,198,188,100]. Sustainability, ESG compliance, and resource efficiency are embedded in operational practices, creating intelligent, adaptive, and human-centered smart manufacturing organizations (Bai et al., 2020; Frank et al., 2019; Ghobakhloo, 2020; Khan et al., 2021; Yang & Shen, 2023; Hu et al., 2024; Yu et al., 2021; Zhao & Yang, 2023) [22,71,76,122,235,102,237,240].

2.3. Review of Management 4.0 in Smart Manufacturing Organizations

Management 4.0 extends digital transformation beyond production to enterprise-wide management functions, emphasizing agility, adaptability, transparency, and innovation across the value chain (Nosalska et al., 2020; Sader et al., 2019; Vrchota et al., 2020) [166,187,225]. Unlike Organization 4.0, which prioritizes automation and workflow efficiency, Management 4.0 focuses on strategic deployment of digital solutions—ERP, CRM, BI, DMS, workflow, and RPA—across operations,

administration, and decision-making. These systems enable real-time information flows, predictive analytics, scenario planning, and cross-functional coordination, empowering senior management to design adaptive structures, optimize processes, allocate resources, and make evidence-based decisions (Szabó, 2024; Chen et al., 2025) [212,42].

The technological foundation includes AI for predictive analytics, VR/AR for immersive training, IoT/IIoT for monitoring, robotics for precision tasks, digital twins for simulation, and additive manufacturing for innovation, creating self-regulating, interconnected, human-centered systems (Haleem et al., 2023; Galaske et al., 2017; Schleich et al., 2018; Ansari, 2019; Kans & Ingwald, 2016a; Frazzon et al., 2019; Fatimah et al., 2020; Dolgui et al., 2022) [94,73,195,15,115,72,61,54].

Integration improves operational efficiency, predictive maintenance, simulation-based planning, lean-agile production, and cloud-enabled decision-making (Saucedo-Martínez et al., 2018; Dicuonzo et al., 2019; Yang et al., 2018; Niesen et al., 2016; Rahardja et al., 2019) [194,50,234,164,181]. Human capital is central: employees shift from execution to analytical, problem-solving, and strategic roles, fostering engagement and knowledge-intensive work (Ivanov et al., 2021; Fatimah et al., 2020; Fettermann et al., 2018; Simion et al., 2018; Neumann et al., 2018; Haleem et al., 2019; Kazancoglu et al., 2021) [104,61,68,203,161,93,120].

Supply chain and logistics are adaptive, resilient, and intelligent, with automation and human oversight balanced (Guo et al., 2020; Borowski, 2021) [90,30]. Industrial Data Spaces and blockchain ensure secure, transparent, and autonomous operations (Jäger et al., 2016; Shamim et al., 2017; Viriyasitavat et al., 2020; Koh et al., 2019) [106,201,223,124]. Cybersecurity is critical due to IoT, cloud, and autonomous system integration, mitigated by edge computing and integrated IT/OT strategies (Michard et al., 2019; Gentner, 2016; Nienke et al., 2017; Guo et al., 2021) [150,75,163,91].

Management 4.0 enhances operational visibility, responsiveness, workforce empowerment, AI/ML adoption, and innovation, supporting wearables, AR, and blockchain to improve safety, task guidance, and data integrity (Shamim et al., 2016; Wulfsberg, 2017; Piccarozzi et al., 2018; Schmidt et al., 2020; Chiarini et al., 2020; Olsen et al., 2020; Rother et al., 2020; Fernández-Caramés et al., 2019; Gunasekaran, 2019) [200,231,177,196,44,169,186,65,89].

Quality management leverages CPS, IoT, ERP, and analytics for predictive and real-time process optimization (Elsisi et al., 2021; Hecklau et al., 2017; Villalba-Diez et al., 2019; Kans & Ingwald, 2016b; Yu et al., 2021; Zaidin et al., 2018; García & García, 2019) [58,98,222,116,237,235,74].

Despite adoption, gaps remain in fully integrated management systems, workforce adaptation, and strategic decision-making, requiring research on technology-human integration, agile practices, and long-term organizational impacts. Management 4.0 represents adaptive, intelligent, and resilient management, offering significant opportunities for research, innovation, and practical implementation in smart manufacturing (Pasi et al., 2020; Ooi et al., 2023) [175,171].

3. CHALLENGES AND RESEARCH GAPS ANALYSIS

The adoption of Management 4.0 in smart manufacturing organizations presents complex, multi-dimensional challenges across technological, human, organizational, governance, and strategic domains. While Industry 4.0 technologies and digital transformation enable agility, resilience, operational intelligence, and sustainable competitiveness, enterprise-wide integration introduces interdependencies that require a coordinated and holistic approach. Success depends on aligning processes, workforce capabilities, governance mechanisms, and strategic objectives (Mohamed, 2018; Müller et al., 2018; Nguyen et al., 2023; Karuppiah et al., 2023; Ojubanire et al., 2026) [153,157,162,118,168]. Table 2 summarizes ten critical dimensions linking challenges, research gaps, and strategic implications. The discussion below elaborates on each dimension, offering insights for scholars and practitioners navigating the adoption of Management 4.0.

- 1) **Technological Integration:** Integrating AI, IoT, robotics, RPA, CPS, digital twins, cloud computing, and legacy systems into cohesive smart manufacturing ecosystems involves significant

challenges. These include ensuring interoperability, managing complexity, maintaining data quality, scaling infrastructure, and securing systems against cyber threats. Research on the combined effects of multi-technology adoption on performance, resilience, and human-machine collaboration remains limited. Strategically, organizations should implement modular and scalable architectures, staged integration processes, and AI-driven real-time analytics to enable predictive decision-making and adaptive operational management (Shahadat et al., 2023; McDermott et al., 2024) [199,148].

- 2) **Organizational & Cultural Dimensions:** Management 4.0 adoption requires structures, norms, and cultures that support agility, innovation, and digital practices. Resistance to change, siloed departments, limited knowledge sharing, and weak innovation culture are persistent challenges. Few studies explore organizational and cultural enablers for large-scale adoption. Organizations should foster cross-functional collaboration, embed knowledge-sharing mechanisms, promote continuous innovation, and cultivate a culture of experimentation and digital literacy to enhance adaptability and organizational resilience (Westerman et al., 2014; Omol et al., 2024; Makori & Omani, 2026) [229,170,141].
- 3) **Managerial & Workforce Capabilities:** Human capital is central to Management 4.0. Key challenges include gaps in digital literacy, adaptive thinking, data-driven decision-making, and leadership readiness for autonomous systems. Research on workforce reskilling, managerial adaptation, and performance outcomes in integrated smart manufacturing contexts is limited. Organizations should invest in structured learning programs, develop digital leadership, redefine roles, and align workforce capabilities with technological and strategic objectives. Promoting knowledge-intensive work and participative decision-making enhances engagement, innovation, and organizational responsiveness (Tashtoush et al., 2023; Kelly et al., 2023; Haleem et al., 2023) [214,121,94].
- 4) **Governance & Ethics:** Robust governance and ethical frameworks are essential for responsible, transparent, and compliant technology deployment. Challenges include ambiguities in AI decision-making, evolving regulatory requirements, accountability gaps, and fragmented governance structures. Limited research examines comprehensive frameworks integrating ethics, compliance, and operational decision-making. Organizations should embed governance into operational processes, define ethical AI guidelines, implement monitoring mechanisms, and ensure regulatory alignment to foster transparency, trust, and sustainable adoption (Guo et al., 2021; Fernández-Caramés et al., 2019) [91,65].
- 5) **Cross-Industry & Contextual Variability:** Management 4.0 adoption varies across industries, scales, and regulatory contexts. SMEs face resource limitations, while larger organizations navigate complex supply chains and legacy systems. Comparative studies on sector-specific adoption and contextual adaptation are scarce. Organizations should tailor technology, processes, and governance frameworks to sector-specific requirements, while leveraging cross-industry best practices and benchmarking to enhance efficiency, agility, and strategic outcomes (Ghobakhloo, 2020; Samper et al., 2022) [76,190].
- 6) **Innovation & Risk Management:** Integrating proactive innovation with predictive risk management strengthens competitiveness and resilience. Challenges include reactive risk approaches, slow innovation adoption, and limited predictive capabilities. Research on interconnections between innovation, risk mitigation, and strategic outcomes is limited. Organizations should deploy predictive risk analytics, establish agile innovation pipelines, and leverage real-time insights to accelerate informed decision-making and capitalize on emerging opportunities (Davenport & Ronanki, 2018; Tjahjono et al., 2017) [47,217].
- 7) **Socio-Technical Integration:** Optimal Management 4.0 performance relies on harmonizing human capabilities, technology, and organizational processes. Challenges include skill-technology misalignment, underutilized collaboration tools, and inadequate immersive learning solutions. Multi-level interactions between humans, technology, and organizational design remain underexplored. Organizations should align technology adoption with workforce competencies, integrate collaborative and immersive tools, and cultivate continuous learning ecosystems to enhance engagement, productivity, and adaptability (Ivanov et al., 2021; Fatimah et al., 2020; Haleem et al., 2023) [104,61,94].

- 8) **Data Governance & Analytics:** Enterprise-wide data governance is essential for evidence-based decision-making. Challenges include fragmented data silos, inconsistent quality, limited advanced analytics adoption, and dispersed governance frameworks. Empirical research on structured data governance and its impact on strategic and operational outcomes is limited. Organizations should standardize data governance protocols, deploy AI-driven analytics, and foster a culture of data-driven decision-making to enable predictive insights, optimize operations, and support strategic alignment (Wedel & Kannan, 2016; Davenport & Ronanki, 2018; McAfee & Brynjolfsson, 2012) [228,47,144].
- 9) **Customer-Centricity & Experience:** Digital platforms, analytics, and real-time feedback loops enable enhanced customer engagement, personalization, and responsiveness. Challenges include fragmented customer data, inconsistent engagement, and slow responsiveness to market dynamics. Frameworks linking digital customer experience with operational and strategic performance are underdeveloped. Organizations should leverage AI-enabled analytics, personalize interactions, and align operations with evolving customer expectations to enhance satisfaction, loyalty, and competitive advantage (Chen et al., 2025; Szabó, 2024) [42,212].
- 10) **Sustainability & Social Responsibility:** Embedding ESG principles into operations, strategy, and technology adoption is increasingly critical. Challenges include environmental impact, weak integration of social responsibility, and limited operational sustainability frameworks. Empirical evidence on ESG integration within Management 4.0 is limited. Organizations should leverage IoT, AI, and analytics to monitor ESG metrics, embed sustainability into strategy and operations, and foster responsible practices that enhance resilience, societal impact, and long-term competitiveness (Bai et al., 2020; Khan et al., 2021; Yu et al., 2021) [22,122,237].

In conclusion, addressing these ten dimensions allows organizations to implement Management 4.0 holistically, creating intelligent, adaptive, human-centered, and sustainable smart manufacturing systems. This framework provides a practical roadmap and research agenda, highlighting opportunities to advance understanding of technology-human integration, organizational transformation, governance, and strategic decision-making in Industry 4.0 environments.

Table 2. Management 4.0: Challenges, Research Gaps, and Strategic Implications.

#	Dimension	Challenges	Research Gaps	Strategic Implications
1	Technological Integration	Complexity integrating AI, IoT, robotics, CPS, and legacy systems	Limited evidence linking multi-tech adoption to performance	Build secure, scalable, interoperable systems; use real-time analytics
2	Organizational & Cultural	Resistance to change, silos, weak innovation culture	Sparse research on cultural and structural enablers	Foster agile, collaborative, innovation-driven culture
3	Managerial & Workforce Capabilities	Skills gaps, low digital literacy, limited adaptability	Few studies on workforce reskilling for intelligent systems	Upskill employees; develop digital leadership and adaptive decision-making
4	Governance & Ethics	Ethical AI deployment, regulatory compliance	Limited integrated governance frameworks	Embed ethical AI guidelines; ensure transparency and accountability
5	Cross-Industry & Contextual Variability	Industry-specific barriers, SME constraints	Few comparative sector studies	Tailor strategies to industry context; benchmark best practices
6	Innovation & Risk Management	Reactive risk approaches, slow innovation adoption	Underexplored link between innovation and risk management	Implement predictive analytics; enable agile innovation processes

7	Socio-Technical Integration	Misalignment of people, technology, and processes	Multi-level human-tech-process interactions underexplored	Align technology with workforce skills; integrate collaboration; foster continuous learning
8	Data Governance & Analytics	Data silos, poor quality, limited analytics adoption	Few robust enterprise-wide frameworks	Standardize governance; leverage analytics for evidence-based decisions
9	Customer-Centricity & Experience	Fragmented insights, slow responsiveness	Limited research on digital customer experience	Use real-time analytics; personalize engagement; align operations with customer needs
10	Sustainability & Social Responsibility	Weak ESG integration, limited social responsibility	Scarce research on embedding sustainability	Monitor ESG metrics; integrate sustainable and ethical practices

4. ROADMAP FOR MANAGEMENT 4.0 IMPLEMENTATION IN SMART MANUFACTURING ORGANIZATIONS

Transitioning toward Management 4.0 in smart manufacturing requires a holistic socio-technical transformation that integrates digital technologies, organizational capabilities, process architectures, and governance mechanisms into a unified adaptive system. Building on the gaps identified in Section 3, this roadmap conceptualizes Management 4.0 as a dynamic capability framework that enables organizations to continuously sense opportunities, seize digital value, and transform operations in response to technological, market, and sustainability changes.

Tables 3 and 4, along with Figure 3, present a structured implementation roadmap that progresses from digital maturity assessment and strategic alignment to full organizational transformation through the integration of key enablers, including technology integration, workforce development, agile processes, cultural transformation, governance, ethics, risk management, customer-centricity, performance monitoring, continuous improvement, and knowledge management, ensuring long-term adaptability. Across all stages, KPIs translate strategic objectives into measurable indicators that enable systematic tracking of progress in digital readiness, system integration, workforce capability, innovation performance, customer satisfaction, operational efficiency, compliance, and knowledge utilization.

The roadmap consists of ten interdependent transformation steps spanning technology, people, processes, governance, and ESG dimensions and is inherently iterative, aligning with Industry 5.0 principles of human-centricity, resilience, and sustainability.

Stage 1: Sensing Digital and Cyber-Physical Maturity

- 1) Description: Establishes a structured assessment of digital and cyber-physical capabilities across production systems, data infrastructure, and workforce readiness.
- 2) Main Objective: Identify transformation gaps and assess organizational readiness for Management 4.0 adoption.
- 3) Key Challenges: Legacy infrastructure, fragmented data environments, uneven digital capabilities, and inefficient investments.
- 4) Key Activities: Maturity modeling, digital audits, workforce capability mapping.
- 5) KPIs: Digital maturity index, adoption rate, readiness score.
- 6) Implementation Logic: Integrates technological, organizational, and human dimensions into a unified maturity profile to support evidence-based prioritization.

7) Outcome: Structured readiness baseline enabling phased transformation.

Stage 2: Defining Strategic and ESG-Aligned Transformation Architecture

- 1) Description: Develops an integrated transformation architecture combining operational strategy, digital innovation, and ESG-oriented value creation.
- 2) Main Objective: Align Management 4.0 initiatives with long-term competitiveness and sustainability objectives.
- 3) Key Challenges: Strategic misalignment, competing priorities, and delayed value realization.
- 4) Key Activities: Strategy mapping, ESG integration frameworks, KPI design.
- 5) KPIs: Strategic alignment index, ESG performance score.
- 6) Implementation Logic: Translates strategic intent into a coherent architecture aligning operational, technological, and sustainability objectives through measurable governance mechanisms.
- 7) Outcome: Unified and strategically aligned transformation roadmap.

Stage 3: Developing Scalable Digital-Intelligent Infrastructure

- 1) Description: Establishes the digital backbone of smart manufacturing through AI, IoT, digital twins, edge/cloud computing, robotics, and blockchain technologies.
- 2) Main Objective: Enable real-time monitoring, predictive analytics, and autonomous decision-making.
- 3) Key Challenges: Integration complexity, interoperability constraints, and cybersecurity vulnerabilities.
- 4) Key Activities: Deployment of AI systems, IoT platforms, digital twins, and cloud infrastructure.
- 5) KPIs: System uptime, latency, predictive accuracy.
- 6) Implementation Logic: Builds a scalable and interoperable cyber-physical infrastructure enabling secure connectivity, seamless data exchange, and distributed intelligence.
- 7) Outcome: Integrated and predictive manufacturing infrastructure.

Stage 4: Developing a Cognitive Workforce and Adaptive Leadership

- 1) Description: Enhances workforce capabilities and leadership competencies for AI-augmented and data-driven environments.
- 2) Main Objective: Enable effective human-AI collaboration and adaptive decision-making.
- 3) Key Challenges: Skill gaps, resistance to automation, and organizational inertia.
- 4) Key Activities: Reskilling programs, leadership development, continuous learning systems.
- 5) KPIs: Digital competency index, learning agility score.
- 6) Implementation Logic: Aligns human capability development with technological advancement through continuous learning and adaptive leadership practices.
- 7) Outcome: Digitally capable and adaptive workforce.

Stage 5: Reconfiguring Processes into Intelligent Adaptive Systems

- 1) Description: Transforms traditional workflows into modular, data-driven, and adaptive production systems.
- 2) Main Objective: Enhance operational agility and enable continuous process optimization.
- 3) Key Challenges: Functional silos, rigid workflows, and limited process transparency.
- 4) Key Activities: Process mining, workflow redesign, autonomous production cells.
- 5) KPIs: Cycle efficiency, responsiveness index.

- 6) Implementation Logic: Converts static processes into adaptive systems driven by real-time feedback loops and embedded intelligence.
- 7) Outcome: Flexible and continuously optimized production processes.

Stage 6: Institutionalizing Governance and Ethical AI Systems

- 1) Description: Establishes governance mechanisms ensuring the ethical, secure, and compliant use of AI and autonomous systems.
- 2) Main Objective: Ensure transparency, accountability, and regulatory alignment.
- 3) Key Challenges: Weak governance structures, regulatory ambiguity, and ethical uncertainty.
- 4) Key Activities: AI governance frameworks, compliance systems, and monitoring mechanisms.
- 5) KPIs: Governance maturity index, compliance rate.
- 6) Implementation Logic: Embeds governance as an integral layer within digital systems to ensure continuous oversight, ethical alignment, and accountability.
- 7) Outcome: Trusted and compliant AI-enabled operational environment.

Stage 7: Integrating Predictive Risk and Innovation Systems

- 1) Description: Integrates innovation management with predictive analytics and simulation-based risk assessment.
- 2) Main Objective: Balance innovation development with proactive risk mitigation.
- 3) Key Challenges: Fragmented innovation processes and limited foresight capabilities.
- 4) Key Activities: Scenario modeling, digital twin simulations, innovation analytics.
- 5) KPIs: Resilience index, innovation success rate.
- 6) Implementation Logic: Embeds predictive foresight mechanisms into decision-making processes to enhance resilience under uncertainty.
- 7) Outcome: Resilient and optimized innovation systems.

Stage 8: Enabling Market-Sensing Adaptive Manufacturing

- 1) Description: Aligns production systems with real-time market intelligence and customer demand signals.
- 2) Main Objective: Enable responsive and demand-driven manufacturing systems.
- 3) Key Challenges: Delayed feedback, fragmented customer insights, and weak demand sensing capabilities.
- 4) Key Activities: Demand forecasting, real-time analytics, and co-creation platforms.
- 5) KPIs: Responsiveness index, customer satisfaction score.
- 6) Implementation Logic: Integrates market intelligence into operational systems to enable continuous adaptation to dynamic demand conditions.
- 7) Outcome: Responsive and customer-centric production systems.

Stage 9: Implementing Cyber-Physical Performance Orchestration

- 1) Description: Establishes integrated systems for continuous monitoring and optimization of operational and organizational performance.
- 2) Main Objective: Enable closed-loop operational intelligence.
- 3) Key Challenges: Data latency, fragmented monitoring systems, and limited decision integration.
- 4) Key Activities: AI dashboards, predictive diagnostics, performance analytics.
- 5) KPIs: Efficiency index, downtime reduction rate.
- 6) Implementation Logic: Creates a cyber-physical feedback architecture integrating multi-source data into real-time decision intelligence for system-wide optimization.

7) Outcome: Optimized operations with enhanced efficiency and reduced downtime.

Stage 10: Institutionalizing Knowledge and Learning Intelligence

- 1) Description: Establishes AI-enabled systems for capturing, structuring, and disseminating organizational knowledge.
- 2) Main Objective: Enable continuous learning and organizational scalability.
- 3) Key Challenges: Knowledge silos, loss of tacit knowledge, and limited replication capacity.
- 4) Key Activities: Knowledge repositories, AI-enabled systems, learning analytics.
- 5) KPIs: Knowledge reuse rate, replication index.
- 6) Implementation Logic: Transforms organizational knowledge into a structured asset through continuous capture, codification, and dissemination.
- 7) Outcome: Adaptive and learning-oriented organization capable of scaling best practices.

In conclusion, this roadmap conceptualizes Management 4.0 as a dynamic capability framework integrating sensing, seizing, and transforming mechanisms across digital infrastructure, cognitive workforce systems, adaptive processes, and governance intelligence. By aligning Technology, People, Processes, Governance, and ESG dimensions, organizations evolve into adaptive socio-technical systems capable of continuous optimization and resilience. The integration of real-time analytics, predictive intelligence, and knowledge systems enables sustained competitiveness and supports the transition toward human-centric Industry 5.0 manufacturing ecosystems.

Table 3. Strategic Roadmap Summary for Management 4.0

Step	Focus Area	Challenges / Gaps / Risks	Key Actions
1	Digital Maturity Assessment	Fragmented systems, low digital literacy, resistance to change	Conduct audits, benchmarking, and readiness surveys; prioritize transformation areas
2	Strategic Vision & Alignment	Conflicting priorities, unclear metrics	Facilitate vision workshops, define KPIs, and align initiatives with strategy
3	Technology Architecture	Legacy systems, data silos, cybersecurity risks	Integrate AI, IoT, cloud solutions; ensure interoperability and security
4	Workforce & Leadership Development	Skill gaps, resistance to change	Implement training, leadership development, mentoring, and cross-functional projects
5	Process & Culture Redesign	Rigid hierarchies, siloed workflows	Introduce agile processes, restructure teams, promote a culture of collaboration and innovation
6	Governance & Ethics	Undefined AI ethics, compliance gaps	Develop governance policies, AI ethics frameworks, and monitoring mechanisms
7	Innovation & Risk Management	Unassessed risks, inconsistent innovation	Apply scenario planning, predictive risk assessment, and agile experimentation
8	Customer-Centricity	Fragmented customer data, delayed insights	Deploy analytics, real-time feedback loops, and co-creation initiatives
9	Performance Monitoring & Continuous Improvement	Limited monitoring, delayed feedback	Establish dashboards, track KPIs, perform regular audits, and optimize processes
10	Knowledge Management & Learning	Knowledge silos, poor documentation	Build repositories, conduct review sessions, and share best practices organization-wide

Table 4. Strategic Objectives and KPIs for Smart Management 4.0

Step	Focus Area	Strategic Objective	KPIs	Expected Outcomes
1	Digital Maturity Assessment	Evaluate readiness and identify gaps	Digital maturity index, readiness score	Clear baseline to guide initiatives
2	Strategic Vision & Alignment	Align initiatives with organizational strategy	Alignment index, KPI coverage	Unified strategy and measurable goals
3	Technology Architecture	Build secure, scalable, interoperable systems	System uptime, integration success	Robust, flexible digital foundation
4	Workforce & Leadership	Develop adaptive skills and leadership	Competency scores, training completion	Skilled, agile, and motivated workforce
5	Process & Culture	Foster agility, collaboration, innovation	Cycle-time reduction, collaboration index	Flexible, innovation-oriented culture
6	Governance & Ethics	Ensure accountability, compliance, and ethical practices	Compliance score, ethical adherence	Trusted, responsible management
7	Innovation & Risk Management	Sustain innovation while mitigating risks	Innovation success rate, risk mitigation index	Balanced, resilient innovation pipeline
8	Customer-Centricity	Deliver responsive, value-driven experiences	Customer satisfaction, NPS	Enhanced engagement, loyalty, market responsiveness
9	Performance Monitoring & Improvement	Continuously optimize processes and outcomes	KPI achievement, efficiency metrics	Sustained operational excellence
10	Knowledge & Learning	Institutionalize knowledge sharing and learning	Knowledge utilization, best practice adoption	Adaptive, learning-oriented organization



Figure 3. Roadmap for Smart Management 4.0

5. CONCLUSION AND FUTURE WORK

This study examined the emergence of Management 4.0 and its transformative role in reshaping smart manufacturing organizations under accelerating digital transformation and Industry 4.0 adoption. Management 4.0 is conceptualized as a managerial transformation framework that integrates advanced digital technologies with organizational structures, human capabilities, and governance systems to enable adaptive, intelligent, and data-driven decision-making. While often framed as a linear progression toward managerial enhancement, the findings indicate that its realization is inherently socio-technical, requiring deep structural reconfiguration rather than incremental technological adoption.

The systematic literature synthesis demonstrates that effective implementation depends on a tightly coupled socio-technical and dynamic capability configuration in which technological infrastructure, organizational architecture, managerial capabilities, and workforce transformation co-evolve. However, the literature remains fragmented, with limited theoretical convergence across technological, organizational, and governance perspectives.

Importantly, this review establishes that Management 4.0 is not value-neutral. It embodies a structural tension between technological augmentation and human agency that remains under-theorized. Alongside performance and efficiency gains, it generates systemic risks inherent to AI-enabled organizational environments. These include managerial deskilling, driven by increasing reliance on algorithmic recommendations that may erode experiential judgment; algorithmic bias, arising from opaque models and biased data foundations; surveillance intensification, which reshapes workplace autonomy and power relations through pervasive monitoring; and over-automation, which can reduce organizational reflexivity and increase dependency on algorithmic systems. Collectively, these dynamics signal a transition toward algorithmically mediated governance structures characterized by cognitive dependency and diluted accountability.

Accordingly, governance and ethics must be reconceptualized as embedded design dimensions of socio-technical systems, rather than ex-post compliance mechanisms. This requires integrating transparency, explainability, auditability, and human-in-the-loop control into the architecture of Management 4.0 systems. Similarly, ESG principles remain insufficiently operationalized and should be embedded as intrinsic system design constraints rather than external reporting obligations.

Theoretical Implications: This study advances Management 4.0 as a socio-technical and dynamic capability-based transformation architecture for intelligent manufacturing systems. It integrates fragmented literature into a unified conceptual framework and clarifies interdependencies across technological, organizational, managerial, and governance dimensions. It extends socio-technical systems theory by incorporating AI-enabled decision environments and positioning governance, ethics, and ESG as co-evolving system properties. Importantly, it introduces a dual-tension perspective in which Management 4.0 simultaneously enhances organizational performance while producing structural risks related to autonomy loss, cognitive dependency, surveillance expansion, and algorithmic control asymmetry.

Practical Implications: The proposed framework provides a structured roadmap for aligning digital strategy, organizational redesign, operational processes, and workforce capabilities. While this alignment enhances agility and performance, it also requires embedded safeguards to address over-automation, algorithmic opacity, surveillance escalation, and erosion of human decision authority in complex environments.

Managerial Implications: The framework supports managers in strengthening digital leadership, enabling data-driven decision-making, and improving cross-functional integration in AI-enabled environments. It emphasizes preserving human judgment in high-stakes decisions, ensuring algorithmic accountability, regulating surveillance practices, and balancing efficiency gains with workforce

autonomy, capability retention, and ethical responsibility.

Study Limitations: This study is based on a systematic literature review and conceptual synthesis, which may introduce selection, disciplinary, and publication biases. The absence of empirical validation limits the generalizability of the proposed framework across industries and levels of digital maturity. Future Research Agenda: Future research should focus on specific socio-technical design and governance challenges rather than broad validation efforts:

- 1) Human-AI decision authority structures: How should decision rights be allocated between humans and AI systems to balance efficiency, accountability, and expert judgment?
- 2) Conditions of managerial deskilling: Under what organizational configurations does AI enhance managerial capability versus erode experiential expertise?
- 3) Algorithmic bias emergence and governance: How do bias structures develop in AI-enabled managerial systems, and which governance mechanisms most effectively detect and mitigate them?
- 4) Surveillance and organizational power asymmetries: How does algorithmic monitoring reshape autonomy, trust, and power distribution in digitally intensive organizations?
- 5) Optimal automation boundaries: What is the appropriate balance between automation and human oversight to preserve organizational reflexivity and adaptability?
- 6) Governance-by-design architectures: Which governance models most effectively embed transparency, auditability, explainability, and ethical accountability into AI-driven systems?
- 7) Operational embedding of ESG principles: How can ESG be transformed from an external reporting framework into an intrinsic design parameter of socio-technical systems?
- 8) Long-term organizational transformation: What are the longitudinal impacts of Management 4.0 on organizational learning, institutional trust, workforce identity, and power structures?

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ABBREVIATIONS

Abbreviation	Full Term	Short Definition
AI	Artificial Intelligence	Systems performing tasks requiring human intelligence.
AI/ML	Artificial Intelligence / Machine Learning	Combined AI and ML methods for predictive and adaptive tasks.
AR	Augmented Reality	Digital overlay on the physical world.

BDA	Big Data Analytics	Analysis of large datasets for actionable insights.
CPS	Cyber-Physical Systems	Integration of physical and digital systems.
DT	Digital Twin	Digital replica of a system, process, or asset.
ESG	Environmental, Social, Governance	Framework for ethical and sustainable practices.
IoT	Internet of Things	Network of connected devices exchanging data.
IIoT	Industrial Internet of Things	IoT is applied in industrial and manufacturing systems.
KPI	Key Performance Indicator	Metric to evaluate performance against goals.
ML	Machine Learning	Systems learning and improving from data.
RPA	Robotic Process Automation	Software automating repetitive tasks.
VR	Virtual Reality	Simulated environment for training or visualization.

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