Chapter 3

Beyond Industry 4.0: Enabling Technologies and the Socio-Technical Foundations of Industry 5.0

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Abstract

Industry 5.0 represents a socio-technical and value-oriented reframing of industrial transformation in which digital technologies are assessed not only through efficiency and productivity gains, but also through their contribution to human-centricity, sustainability, and resilience. Rather than replacing the technological foundations of Industry 4.0, this emerging paradigm reinterprets their role within a broader framework of responsible, adaptive, and human-centred industrial development. This chapter examines the enabling technologies and design principles associated with Industry 5.0, arguing that technologies such as digital twins, artificial intelligence, cyber-physical systems, and interoperable digital infrastructures derive their strategic significance not simply from their technical sophistication, but from how they are designed, governed, and embedded in organisational routines. The discussion further shows that the successful implementation of Industry 5.0 depends on more than technological adoption alone; it requires appropriate work design, governance arrangements, accountability structures, and assessment mechanisms capable of translating the three pillars into operational reality. Particular attention is given to issues such as human-in-the-loop oversight, worker-related data governance, interoperability, maturity assessment, and multi-objective performance measurement. By situating Industry 5.0 within the broader evolution of industrial paradigms and analysing its principal implementation challenges, the chapter provides an analytically grounded account of Industry 5.0 as a framework for responsible, resilient, and humanly meaningful industrial transformation.

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1. Introduction

The ongoing digital transformation of industry has profoundly altered the way production systems are designed, monitored, and coordinated. Over the past decade, this transformation has largely been interpreted through the lens of Industry 4.0, with its emphasis on cyber-physical integration, automation, data-driven optimisation, and intelligent manufacturing architectures. While these developments have substantially expanded technological capability, recent discussions increasingly suggest that industrial transformation cannot be evaluated exclusively through productivity, efficiency, and connectivity metrics. Instead, growing attention is being directed toward the broader consequences of digitalisation for human work, sustainability performance, governance, and systemic adaptability under conditions of disruption and uncertainty (Asif et al., 2023; Choi et al., 2022)

In this context, Industry 5.0 has emerged as an important reframing of industrial development. Rather than denoting a simple chronological stage after Industry 4.0, it reflects a shift in emphasis from technology deployment alone to the alignment of technological systems with broader socio-technical objectives. This shift is especially visible in the increasing prominence of three interrelated principles, human-centricity, sustainability, and resilience, which collectively redefine how industrial progress is understood and assessed. From this perspective, the question is no longer only how advanced digital systems can become, but also how they can be organised and governed to support meaningful human participation, environmentally responsible production, and adaptive responses to volatility and disruption (Tallat et al., 2024).

Technological continuity remains a central feature of the transition toward Industry 5.0. Rather than abandoning the technological foundations established under Industry 4.0, the emerging literature increasingly reframes their function, orientation, and conditions of use. In this context, technologies such as AI-enabled decision systems, digital twins, and connected cyber-physical infrastructures continue to occupy a pivotal role; however, their significance is no longer defined solely by their optimisation capacity. Instead, they are increasingly assessed in relation to safer human–machine collaboration, interoperable and reconfigurable system architectures, and governance mechanisms capable of addressing worker-related data, accountability, and explainability. Research on human digital twins and human-aware cyber-physical systems, for example, suggests that human-centricity is becoming operationalised through models that incorporate workload, ergonomic risk, and human constraints into decision loops rather than treating them as external compliance concerns (Coronado et al., 2024). Similarly, work on interoperable digital infrastructures highlights that modularity and standards-based integration are critical not only for efficiency, but also for resilience and scalable industrial adaptation (Eirinakis et al., 2024).

The practical realisation of Industry 5.0 depends on considerably more than the mere adoption of advanced technologies. What is increasingly emphasised in the literature is that the transformative potential of these technologies is shaped by the organisational and governance contexts in which they are embedded. Digital systems may be technically sophisticated, yet still fall short of Industry 5.0 objectives when they are introduced without corresponding changes in decision architectures, work design, accountability structures, and performance evaluation frameworks. From this perspective, human-in-the-loop oversight, explainable AI interfaces, and transparent data governance emerge not as peripheral concerns, but as essential conditions for ensuring that digital transformation remains compatible with safety, legitimacy, and worker well-being in practice (Senoner et al., 2024; Yan et al., 2025). In parallel, sustainability-oriented research underscores the importance of monitoring and optimisation approaches that extend beyond operational efficiency to address energy consumption, material use, and lifecycle implications across industrial systems (Tallat et al., 2024).

Against this background, this chapter examines the enabling technologies and design principles associated with Industry 5.0, with particular emphasis on how they contribute to the operationalisation of human-centricity, sustainability, and resilience in industrial contexts. It argues that Industry 5.0 should be understood as an integrative socio-technical framework in which industrial intelligence is evaluated not solely by what technologies can optimise, but by the kinds of work systems, governance arrangements, and long-term value outcomes they help produce. To develop this argument, the chapter first situates Industry 5.0 in relation to earlier industrial paradigms, then analyses the main enabling technologies associated with this transition, and finally discusses implementation requirements related to governance, work design, and assessment. In doing so, it seeks to provide a more analytically grounded account of Industry 5.0 as a framework for responsible and adaptive industrial transformation.

The remainder of this chapter is organised as follows. Section 2 situates Industry 5.0 within the historical evolution of industrial revolutions and clarifies its conceptual foundations. Section 3 examines the enabling technologies and design principles associated with Industry 5.0, beginning with its digital backbone and then discussing pillar-aligned enablers related to human-centricity, sustainability, and resilience. Section 4 addresses implementation challenges, governance requirements, and assessment approaches. Finally, Section 5 concludes the chapter.

2. Background

2.1. From Mechanisation to Digitalisation: Industry 1.0–3.0

In the economic history and innovation studies literature, industrial revolutions are frequently interpreted as long waves of technological transformation that reshape production systems, labour relations, and institutional arrangements. Rather than being purely technological milestones, these transitions represent socio-technical shifts in which technological change interacts with organisational structures, knowledge systems, and economic institutions (Maddikunta et al., 2022). Industry 1.0 is typically associated with the mechanisation of production through water and steam power and the emergence of factory systems. The transition from craft production to mechanised manufacturing significantly increased productivity and altered the structure of labour and economic organisation. Contemporary scholarship highlights that the significance of this transformation lies not only in technological innovation but also in the restructuring of production processes and labour systems (Xu et al., 2021; Zhong et al., 2017).

Industry 2.0 emerged with the widespread adoption of electricity, assembly lines, and mass production techniques. Electrification enabled more flexible factory layouts and improved productivity, while the introduction of assembly lines facilitated large-scale standardised manufacturing. These developments significantly accelerated industrial productivity and expanded global industrial production (Zhong et al., 2017) (Lu, 2017). Industry 3.0, often described as the digital revolution in manufacturing, was characterised by the introduction of electronics, information technology, and automation into industrial production. The diffusion of programmable logic controllers (PLCs), computer-aided design (CAD), and computer-integrated manufacturing (CIM) systems enabled automated production and more efficient control of manufacturing processes. This transition marked the beginning of digitally supported industrial production systems and laid the technological foundation for subsequent digital manufacturing paradigms (Lu, 2017; Xu et al., 2021).

2.2. Industry 4.0: Cyber-Physical Production And the Smart Factory

Industry 4.0 is widely described as the convergence of digital and physical systems in industrial contexts, with the aim of creating smart products, processes, and factories. A canonical synthesis defines Industry 4.0 as a manufacturing paradigm in which advanced information systems, automation, and connectivity support new forms of value-chain integration and real-time decision-making (B. E. Narkhede et al., 2023; Sony et al., 2021). A complementary stream of research operationalises this paradigm through design principles and technical building blocks such as interoperability, decentralised decision-making, virtualisation, and real-time capability (Parhi et al., 2022). Across review studies, Industry 4.0 is typically positioned as an ecosystem of enabling technologies such as the industrial internet of things, cyber-physical systems, cloud/edge computing, digital twins, and industrial analytics—intended to improve flexibility, transparency, and performance (B. E. Narkhede et al., 2023; Senna et al., 2023).

At the same time, the Industry 4.0 literature documents persistent challenges that are not purely technical. First, digital transformation is frequently constrained by organisational readiness such as skills, change management capabilities, and governance structures that can align technology investments with operations strategy (Frank et al., 2019; Lu, 2017). Second, Industry 4.0 can introduce new risks related to system complexity, cybersecurity, and reliability in tightly coupled production networks (Zhong et al., 2017). Third, and crucially for the transition toward Industry 5.0, Industry 4.0 initiatives have been criticised for over-emphasising technology-driven productivity narratives while under-specifying worker well-being, job design, and social sustainability outcomes (Atif, 2023; Sarkar et al., 2024; Xu et al., 2021).

2.3. Why Industry 5.0: human-centricity, sustainability, and resilience

Industry 5.0, introduced by European Commission (Breque et al., 2021), is increasingly discussed as a value-oriented evolution of digital industrial transformation, less a rejection of Industry 4.0 technologies than a re-interpretation of their purpose and governance. Scholarly contributions commonly converge on three interrelated pillars: human-centricity, sustainability, and resilience (Maddikunta et al., 2022; G. B. Narkhede et al., 2025). In this view, advanced automation is not framed primarily as a substitute for labour, but as a complement to human capabilities, supporting creativity, problem solving, and safer work in complex environments (Maddikunta et al., 2022; Nahavandi, 2019).

This orientation aligns with contemporary socio-technical perspectives on digital transformation, which emphasise that organisational performance and worker outcomes emerge from the interaction between technological systems, organisational structures, and human capabilities (Ghobakhloo et al., 2025). From this viewpoint, purely technology-driven initiatives may optimise technical efficiency while overlooking broader system-level outcomes such as worker autonomy, learning opportunities, and long-term organisational adaptability. As digital technologies such as artificial intelligence, advanced analytics, and intelligent automation become increasingly integrated into industrial systems, these concerns become more prominent because technological change reshapes job boundaries, required skill profiles, and workplace dynamics (Reiman et al., 2021).

The sustainability dimension of Industry 5.0 builds on contemporary research in sustainable and circular manufacturing, which emphasises reducing resource intensity, minimising waste and emissions, and incorporating lifecycle thinking into production systems and product design. In this context, sustainability is not limited to environmental performance alone but also includes social and economic considerations, suggesting that industrial transformation should be evaluated against broader societal objectives rather than purely productivity-based indicators (Ghobakhloo et al., 2025; Rejeb et al., 2025). These perspectives also resonate with recent discussions on sustainable industrial development that emphasise aligning technological progress with environmental constraints and responsible innovation practices (Maddikunta et al., 2022; Xu et al., 2021). The resilience dimension has gained increasing attention in recent years, particularly in light of global disruptions affecting supply chains and manufacturing systems. In operations and supply chain research, resilience is generally conceptualised as the capability of industrial systems to anticipate, respond to, and recover from disruptions while maintaining operational continuity (Ivanov, 2023). Recent studies further argue that resilient manufacturing systems must integrate digital technologies with organisational capabilities such as adaptive decision-making, knowledge sharing, and rapid system reconfiguration in order to remain viable under prolonged uncertainty (Ivanov, 2023). Taken together, the Industry 5.0 discourse can be interpreted as a response to the recognised asymmetries of Industry 4.0: while digitalisation can enhance efficiency and responsiveness, it does not automatically deliver humane work, sustainable outcomes, or resilient industrial ecosystems.

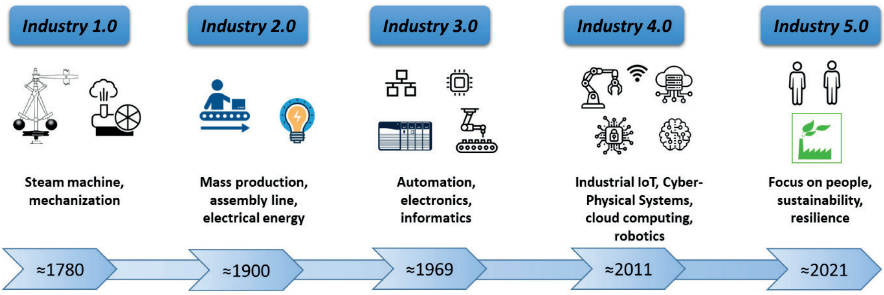

Figure 1 Timeline of Industrial Revolutions (adapted from (Folgado et al., 2024))

3. Enabling Technologies and Design Principles for Industry 5.0

Industry 5.0 is commonly conceptualised as a value-oriented reconfiguration of digital industrial transformation, not as a replacement of Industry 4.0 technologies but as a shift in their purpose and governance toward human-centricity, sustainability, and resilience (Jiménez Rios et al., 2024). In this framing, enabling technologies are best understood as means to operationalise socio-technical objectives rather than as ends in themselves, implying that technological progress must be assessed through multi-dimensional value creation rather than productivity alone (Jiménez Rios et al., 2024). Consequently, the same technology can yield markedly different outcomes depending on how it is designed, governed, and embedded in work practices and organisational routines, particularly where AI-enabled decision support, automation, and monitoring reshape work organisation, roles, and skills (Li et al., 2023; Pasman & Behie, 2024).

3.1. Digital Backbone: Connectivity, Cyber-Physical Integration, and Digital Twins

Most Industry 5.0 deployments presuppose a technical foundation inherited from Industry 4.0: industrial connectivity, cyber-physical integration, and data infrastructures that support real-time monitoring and analytics. Within this backbone, digital twins have gained particular prominence because they integrate data, models, and operational context into a shared decision space for monitoring, simulation, and control (Barata & Kayser, 2024). Recent evidence syntheses argue that digital twins can be leveraged to address, in an integrated manner, the three Industry 5.0 pillars by (a) supporting operator assistance and safer work design, (b) enabling sustainability-oriented optimisation (e.g., energy and resource flows), and (c) strengthening resilience through what-if analyses and disruption-response planning (Lv, 2023). However, the contribution of digital twins depends on design scope and governance. Twin-based insights translate into Industry 5.0 outcomes only when models are interoperable, validated for decision use, and embedded into organisational routines with clear accountability for acting on recommendations especially when human factors and safety constraints are involved. Thus, digital twins function less as a standalone technology and more as an enabling infrastructure for socio-technical decision-making in Industry 5.0 (Barata & Kayser, 2024; Pasman & Behie, 2024).

3.2. Pillar-aligned enabling technologies

3.2.1. Human-centricity Enablers

Human-centric Industry 5.0 emphasises human–machine complementarity, where advanced automation augments human capability and improves the quality and safety of work. Beyond generic "cobot" narratives, recent manufacturing research proposes human-centric adaptive manufacturing in which human skills and system capabilities co-evolve through multi-level adaptation and on-site upskilling mechanisms, supported by optimisation and AI. This stream highlights that human-centricity is not merely an interface issue; it is a production-system design logic in which system reconfigurability and human versatility are treated as joint assets (Li et al., 2023). A second, rapidly developing direction concerns human digital twins and human-aware cyber-physical systems that model human states, constraints, and capabilities for safer collaboration and improved decision support. Reviews of human digital twins in Industry 5.0 outline enabling technologies (e.g., sensing, modelling, and inference pipelines) and identify key challenges related to validity, privacy, and integration into operational decision loops (Bucci et al., 2025). These approaches provide a pathway to operationalise human-centricity via measurable signals (e.g., workload proxies, task risk, and collaboration constraints), while also raising governance requirements for worker-related data and algorithmic accountability (Pasman & Behie, 2024).

3.2.2. Sustainability Enablers

The sustainability pillar is increasingly linked to digital capabilities that strengthen measurement transparency (energy and material monitoring), enable simulation-driven optimisation (e.g., energy-aware scheduling and process parameter exploration), and support lifecycle-oriented decisions that avoid burden shifting across stages of production and supply networks (Tallat et al., 2024). In this context, digital twins are positioned as a sustainability enabler because they allow firms to experiment virtually, evaluate alternative interventions, and compare scenarios before physical implementation—thereby reducing trial-and-error costs and accelerating learning cycles (Barata & Kayser, 2024).

3.2.3. Resilience Enablers

Resilience in Industry 5.0 is increasingly treated as an adaptive capability encompassing anticipation, response, recovery, and reconfiguration under uncertainty. Here, enabling technologies include disruption-aware analytics and digital twins for stress testing, contingency planning, and identifying recovery pathways under alternative disruption scenarios (Lv, 2023). In addition, operations-management research has emphasised that the broader landscape of "disruptive technologies" creates both opportunities and new coordination risks, strengthening the need for resilience-by-design in industrial systems (Choi et al., 2022). A distinctive Industry 5.0 contribution is to link resilience to human safety and well-being under digitally mediated work. As automation and AI expand, risk profiles change, increasing the relevance of governance mechanisms that consider psychosocial stress, workload, and human control in AI-steered processes. "Safety 5.0" discussions connect resilience to safety management, ESG expectations, and the need for socio-technical risk governance that extends beyond technical redundancy (Pasman & Behie, 2024). As a result, resilience enablers in Industry 5.0 include not only digital tools but also organisational learning, decision rights, and safety-accountability structures that determine how systems adapt during disruption (Choi et al., 2022).

3.3. Design principles: what makes a deployment Industry 5.0–consistent?

Industry 5.0–consistent deployments require more than adopting advanced technologies; they require explicit design principles that shape how technologies are integrated into work systems, how decisions are made, and how accountability is maintained across human–machine interactions (Wang et al., 2024; Yan et al., 2025). In practice, these principles function as "translation mechanisms" that connect digital capabilities to the value pillars of human-centricity, sustainability, and resilience.

First, human-in-the-loop decision architectures become essential whenever AI affects safety-critical or high-consequence decisions such as task allocation, quality release, or scheduling. Rather than treating oversight as a generic requirement, operational designs increasingly specify decision thresholds, escalation paths, and verification interfaces, supported by explainability features that enable domain experts to interpret, validate, and override algorithmic outputs when needed (Senoner et al., 2024; Yan et al., 2025).

Second, safety and well-being by design requires modelling human constraints as system requirements, not as downstream compliance checks. Human-aware digital representations—particularly human digital twins—are increasingly proposed to represent human states and constraints within cyber-physical decision loops, enabling safer human–robot collaboration and more context-sensitive planning (Coronado et al., 2024). These approaches also make it possible to reason about fatigue, workload, and ergonomic risk as first-class variables in operational optimisation (Wang et al., 2024).

Third, interoperability and modularity are central to scalability and resilience. Industry 5.0 deployments must avoid "isolated islands" of optimisation by enabling the exchange of models, semantics, and control signals across heterogeneous assets and organisational boundaries. Standards-oriented and interoperable digital twin approaches are increasingly highlighted as practical routes to integrability and rapid reconfiguration in distributed and modular manufacturing settings (Eirinakis et al., 2024).

Finally, Industry 5.0–consistent design implies governance in practice, particularly where worker-related data and AI-enabled monitoring are involved. Credible human-centricity depends on transparent data governance arrangements (roles, accountability, quality controls, and purpose limitation) and organisational safeguards that mitigate risks associated with pervasive monitoring and algorithmic coordination (Bernardo et al., 2024; Zhang et al., 2025).

4. Implementation Pathways and Assessment for Industry 5.0

Implementing Industry 5.0 requires translating the three pillars—human-centricity, sustainability, and resilience—into operational targets, capability-building programs, and governance mechanisms that shape how digital technologies are deployed in production and across supply networks. Recent roadmap-oriented research emphasises that Industry 5.0 progress is rarely achieved through isolated technology projects; instead, it depends on coordinated changes in strategy, processes, skills, and decision rights that align digital capabilities with multi-dimensional value creation (Ghobakhloo et al., 2024). A practical implementation logic can be structured as a staged pathway:

i. Baseline and scoping (current-state diagnosis and priority setting),

ii. Capability building (data/automation backbone plus pillar-aligned applications),

iii. Embedding and scaling (work redesign, governance, and learning loops),

iv. Continuous improvement (multi-objective performance management and maturity re-assessment).

This staged view is consistent with recent discussions that position Industry 5.0 as a socio-technical transformation rather than a purely technological upgrade (Ali et al., 2025; Ghobakhloo et al., 2024).

A persistent implementation challenge is that Industry 5.0 places stronger requirements on governance than typical Industry 4.0 programs, particularly when worker-related data, AI-enabled decision support, and monitoring systems are introduced. Safety- and responsibility-oriented work highlights the need for explicit governance arrangements that define purpose limitation, accountability, and organisational safeguards so that human-centricity is credible in practice (Pasman & Behie, 2024). Implementation research also suggests that skills and work design are not secondary concerns but core enablers of Industry 5.0. Human-centricity implies participatory design and capability development so that new technologies augment rather than deskill the workforce; resilience similarly depends on organisational learning and adaptive coordination routines rather than redundancy alone (Ali et al., 2025).

Because Industry 5.0 is explicitly multi-objective, evaluation requires expanding measurement beyond traditional productivity metrics to include indicators for worker well-being, sustainability performance, and resilience capability. Recent work has begun to operationalise this shift via KPI sets and performance frameworks tailored to Industry 5.0 contexts. For example Mohammed et al. (2025) identify KPI families that integrate sustainability and resilience dimensions alongside operational performance in logistics/ warehousing settings.

A pragmatic approach for organisations is to implement a balanced measurement architecture with three layers:

- Operational layer: throughput, quality, downtime, energy intensity;
- Pillar layer: (i) human-centricity (safety incidents, ergonomic risk proxies, training/skill development, perceived autonomy), (ii) sustainability (energy and material footprints, emissions intensity, waste/rework, circularity rates), (iii) resilience (time-to-recover, disruption response time, flexibility/reconfigurability proxies);

- Governance layer: auditability of AI decisions, compliance with data governance rules, and effectiveness of participation/feedback mechanisms (Asif et al., 2023; Yadav et al., 2025).

Implementation efforts can fail not because enabling technologies are unavailable, but because deployments are misaligned with socio-technical requirements and value objectives. One common failure mode is technology-first deployment, where organisations install tools without redesigning work processes, decision rights, and accountability structures, resulting in limited adoption, shallow use, or legitimacy concerns among employees and other stakeholders (Ali et al., 2025). A second failure mode concerns metric mismatch: when success continues to be assessed primarily through productivity and efficiency indicators, initiatives may implicitly incentivise designs that erode human-centric outcomes or deprioritise sustainability goals, even if these are stated as strategic objectives (Mohammed et al., 2025). A third risk involves governance gaps, particularly in AI-enabled decision support and worker-data practices; unclear accountability and insufficient safeguards can undermine trust, create safety and compliance risks, and weaken organisational acceptance of digital transformation (Pasman & Behie, 2024). Finally, resilience blind spots can emerge when tightly coupled systems are engineered for maximal efficiency without ensuring reconfigurability, disruption-ready routines, or appropriate redundancy, thereby increasing vulnerability to shocks and delaying recovery when disruptions occur (Choi et al., 2022).

To manage implementation as a multi-year transformation, organisations increasingly use maturity models to (i) diagnose current readiness, (ii) define target capabilities, and (iii) sequence initiatives. Recent contributions propose Industry 5.0-specific maturity models that explicitly assess progress across sustainability, resilience, and human-centricity rather than limiting assessment to digital readiness (Latino, 2025). Complementary work reviews how Industry 4.0 maturity models do (or do not) capture Industry 5.0 requirements, highlighting gaps in human-centric and resilience dimensions and calling for updated assessment constructs (Hein-Pensel et al., 2023). Maturity assessment for Industry 5.0: A review of existing maturity models (Reyes Domínguez et al., 2025, 2026). From an implementation standpoint, maturity models are most useful when paired with (a) evidence-based scoring, (b) pillar-specific roadmaps, and (c) review cycles that connect maturity updates to investment decisions and governance improvements (Ghobakhloo et al., 2024; Latino, 2025; Reyes Domínguez et al., 2026).

5. Conclusion

Industry 5.0 should be understood not as a linear successor that displaces Industry 4.0, but as a socio-technical and normative reframing of industrial transformation. Its distinctive contribution lies in shifting the analytical and practical centre of gravity from technology adoption per se to the purposes, governance arrangements, and value logics through which digital technologies are deployed. In this respect, the chapter has shown that the enabling technologies commonly associated with contemporary industrial transformation such as cyber-physical systems, artificial intelligence, advanced automation, and digital twins retain their relevance in the Industry 5.0 era; however, their significance is no longer exhausted by gains in efficiency, speed, or connectivity alone. Rather, their strategic value must be assessed in terms of their capacity to support human-centric work systems, sustainability-oriented production, and resilient organisational and supply network configurations.

From this perspective, the chapter underscores that human-centricity, sustainability, and resilience are best interpreted not as parallel policy aspirations, but as mutually constitutive dimensions of a broader transformation logic. Human-centred design is not simply an ethical supplement to digitalisation; it is a condition for adaptive capacity, legitimacy, and durable organisational learning. Likewise, sustainability cannot be reduced to resource-efficiency metrics alone, since it also requires lifecycle awareness, responsible innovation, and the alignment of industrial performance with broader environmental and social objectives. Resilience, in turn, extends beyond technical redundancy or disruption recovery narrowly defined, and must be understood as an adaptive capability grounded in reconfigurability, governance readiness, human competence, and safe human–machine collaboration. Taken together, these observations suggest that Industry 5.0 is most convincingly conceptualised as an integrative framework in which industrial intelligence is evaluated according to the quality of its socio-technical embedding rather than the sophistication of technological artefacts alone.

A further conclusion emerging from the literature is that many implementation difficulties associated with Industry 5.0 do not stem primarily from technological insufficiency, but from socio-technical misalignment. Technology-first deployment strategies, narrow productivity-centred evaluation systems, weak governance of AI-enabled decision support, and insufficient attention to work redesign can all undermine the transformative claims of Industry 5.0 in practice. Accordingly, successful implementation requires more than the acquisition of advanced tools; it depends on the coordinated development of capabilities, organisational routines, participation mechanisms, and accountability structures that translate the three pillars into operational reality. In this sense, Industry 5.0 is not a discrete innovation programme, but a multi-layered organisational transformation in which strategy, skills, governance, and performance measurement must evolve together.

The chapter also indicates that one of the most important unresolved issues in the emerging Industry 5.0 literature concerns operationalisation. Although the discourse around the three pillars has become increasingly coherent at the conceptual level, further empirical and methodological work is needed to specify robust indicators, maturity models, and comparative assessment frameworks capable of capturing trade-offs among efficiency, worker well-being, sustainability performance, and resilience capacity. This is especially important because the credibility of Industry 5.0 as a framework depends not only on normative appeal, but also on the extent to which its principles can be translated into measurable and governable organisational practices across sectors and institutional contexts. Future research should therefore move beyond descriptive advocacy and give greater attention to implementation pathways, governance design, and context-sensitive evidence on how firms negotiate the tensions inherent in multi-objective industrial transformation.

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