Industry 4.0 to 5.0: A Socio-Technical Transformation towards Human-Centric and Sustainable Manufacturing

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Abstract: The ongoing industrial transformation, Industry 4.0, integrates cyber-physical systems, IoT/IIoT, cloud–edge infrastructures, AI/ML, robotics, and digital twins into manufacturing and supply-chain environments. This paper presents a critical, systematic literature review of 45 peer-reviewed articles (2013–2024) following PRISMA guidelines. We synthesize the conceptual foundations, enabling technologies, applications, benefits, and challenges, and critically assess the transition to Industry 5.0.

Evidence indicates that Industry 4.0 delivers measurable improvements: 10–20% gains in equipment utilization, 15–30% reductions in defects, and 20–40% reductions in downtime when technologies are deployed in integrated configurations (IIoT + digital twin + AI). However, five persistent constraints mediate these benefits: cybersecurity vulnerabilities, high implementation costs (disproportionately affecting SMEs), workforce skills gaps, interoperability deficits, and governance/policy fragmentation.

Significant contradictions in the literature are identified. While some studies report ROI exceeding 30%, fewer than 50% of manufacturing firms achieve positive returns from fragmented deployments. Pilot-to-scale failure is widely acknowledged but rarely quantified. Sustainability claims require rigorous lifecycle assessment due to rebound effects.

Industry 5.0 reorients the trajectory toward human-centricity, sustainability, and resilience. However, it remains conceptually fragmented, policy-driven rather than empirically grounded, with speculative claims about 6G (TRL 2–3) and quantum computing (TRL 1–2). Priority research gaps include longitudinal ROI studies, socio-technical metrics, and comparative policy experiments. This review contributes a critical synthesis and strategic recommendations for academia, industry, and policymakers to achieve equitable and sustainable industrial transformation.

Keywords: Industry 4.0, Cyber-Physical Systems (CPS), Internet of Things (IoT) / Industrial Internet of Things (IIoT), Digital Twin (DT), Artificial Intelligence (AI) & Machine Learning (ML), Industry 5.0, Socio-technical systems

1. Introduction

The global manufacturing and industrial landscape is transforming, often termed the Fourth Industrial Revolution or Industry 4.0. This transformation integrates cyber–physical systems, pervasive sensing and connectivity (IoT/IIoT), large-scale data analytics, cloud/edge computing, and intelligent decision-making (AI/ML), producing flexible, resilient, and data-driven production systems commonly referred to as smart factories [1], [14].

Industry 4.0 is best understood as the outcome of long-run technological and organizational change; it represents a convergence of mature digital technologies with manufacturing practice, rather than an isolated invention. The literature describes Industry 4.0 both as a technological assemblage (CPS + IoT + AI + digital twin + connectivity) and as a socio-technical shift that requires new organizational capabilities, governance, and workforce skills.

1.1 Evolution: Industry 1.0 to Industry 4.0 (and Industry 5.0)

The concept of Industry 4.0 is best understood not as a sudden rupture but as the latest phase in a long-running co-evolution of technology, production organization, and societal infrastructure. Each successive industrial revolution—from steam-powered mechanization to electrified mass production to computer-driven automation—has introduced distinctive technological paradigms while demanding new forms of work organization, skills, and governance. The evolution of industrial revolutions reflects the progressive integration of technological innovation, production systems, and socio-technical transformation. Table 1 summarizes the major characteristics, technologies, and human roles associated with Industry 1.0 through the emerging Industry 5.0 paradigm.

Table 1: Industrial revolutions – core technologies and organizational shifts

Industrial Revolution	Time Period	Core Technologies	Production Characteristics	Human Role	Key Outcome	Ref.
Industry 1.0	Late 18th century	Steam engine, mechanization, water power	Mechanized production and factory systems	Manual labor support	Transition from agrarian to industrial economy	[1, 11, 12]
Industry 2.0	Late 19th – early 20th century	Electricity, assembly lines, mass production systems	Standardized large-scale manufacturing	Division of labor and specialized work	High-volume production and industrial expansion	[10, 11, 14]
Industry 3.0	Late 20th century	Electronics, computers, PLCs, industrial automation	Automated and programmable manufacturing	Machine supervision and operational control	Improved productivity and precision	[2, 14, 28]
Industry 4.0	Early 21st century	CPS, IIoT, AI/ML, cloud computing, digital twins	Smart, connected, and data-driven manufacturing	Human–machine collaboration	Intelligent and flexible smart factories	[1, 14, 31, 32]
Industry 5.0	Emerging future	Cobots, explainable AI, sustainable technologies, 6G, advanced analytics	Human-centric, resilient, and sustainable production	Human augmentation, creativity, and decision support	Sustainability, resilience, and societal well-being	[3, 19, 33, 45]

Figure 1 illustrated that evolution of industrial revolutions from mechanization and mass production to cyber-physical manufacturing and human-centric Industry 5.0, highlighting technological, organizational, and societal transformations across successive industrial paradigms.

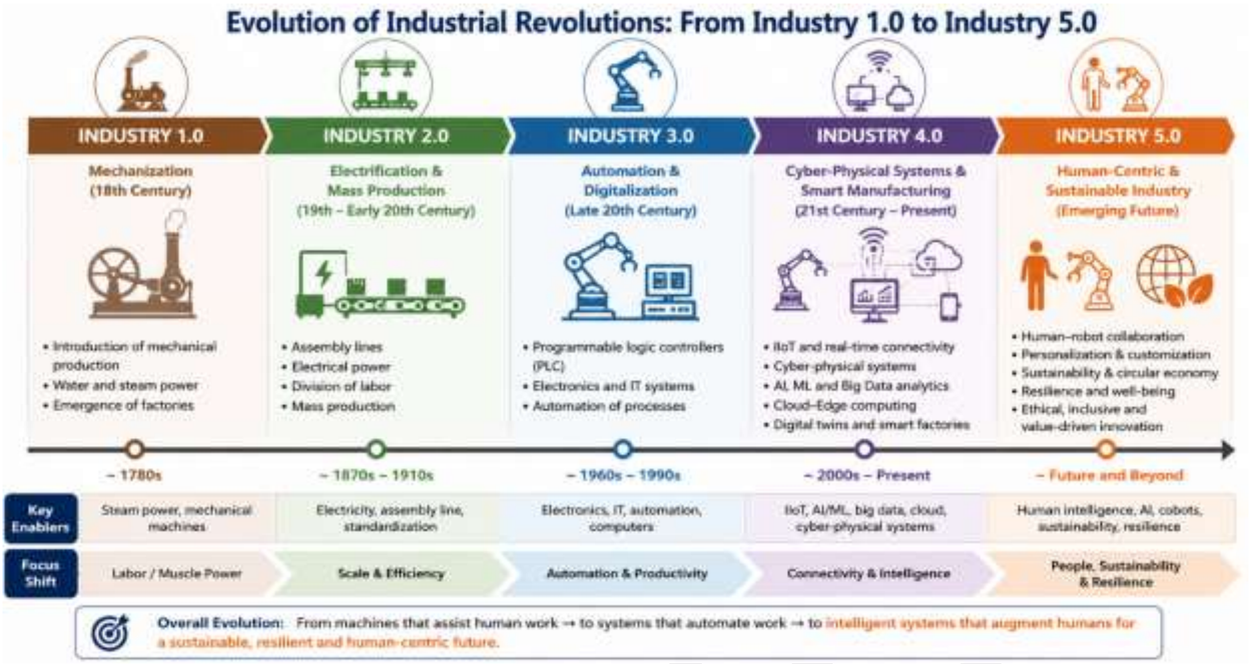

Figure 1: Evolution of Industrial Revolutions from Industry 1.0 to Industry 5.0

1.2 Novelty and Contribution (Explicit Statement)

Existing reviews on Industry 4.0–5.0 transitions [14, 21, 33] have primarily focused on technological taxonomies, enabling technologies, or readiness assessments. However, they lack:

- **Critical evaluation** of contradictions and empirical gaps in the literature
- **Socio-technical integration** that explicitly links technology, organization, and governance as co-evolutionary dimensions
- **Systematic methodology** following established review guidelines (e.g., PRISMA)

Our contribution is threefold:

1. **Methodological:** A PRISMA-guided systematic literature review with transparent search strategy, inclusion/exclusion criteria, and quality appraisal.
2. **Analytical:** A critical synthesis that identifies contradictions (e.g., high ROI claims vs. pilot-to-scale failures), unresolved debates (e.g., Industry 5.0 as paradigm shift vs. rebranding), and evidence gaps.
3. **Conceptual:** A novel Socio-Technical Alignment Model (Synthesis Triangle, Figure 8.1) that integrates technology, organization, and governance as necessary co-evolving dimensions for Industry 4.0→5.0 transition.

1.3 Motivation for Industry 4.0 Adoption

The reviewed literature outlines several interconnected drivers that encourage firms and policymakers to adopt Industry 4.0, with the most prominent being productivity and flexibility gains, mass customization and new business models, resilience and supply-chain agility, sustainability and resource efficiency, and competitive and national strategic interests [1, 14, 23].

1.4 Research Objectives and Scope

Primary objective: To critically synthesize the theoretical, technical, organizational, and policy literature on Industry 4.0, producing a systematic review that defines the state-of-the-art, identifies major technology clusters, highlights organizational and societal implications, and surfaces research gaps.

Specific objectives:

1. Conceptual consolidation of Industry 4.0 definitions, pillars, and reference architectures
2. Technology mapping of core technologies to applications and outcomes
3. Organizational and societal analysis of workforce readiness, governance, and cybersecurity
4. Critical identification of evidence gaps, contradictions, and future research priorities

This review examines conceptual, technical, empirical, and policy literature published between 2013 and 2024, prioritizing manufacturing and supply-chain contexts.

2. Conceptual Foundations of Industry 4.0

This section establishes the theoretical and conceptual grounding of Industry 4.0 as a socio-technical phenomenon. Rather than merely describing definitions and frameworks, we critically evaluate their origins, utility, limitations, and empirical validation.

2.1 Definitions and Global Initiatives

Industry 4.0 lacks a single universally accepted definition. However, a synthesis of the literature suggests that Industry 4.0 is best understood as a socio-technical transformation of manufacturing that integrates cyber-physical systems (CPS), pervasive sensing and connectivity (IIoT), large-scale data analytics (big data/AI), and digital representations of assets (digital twins), enabling decentralized decision-making, flexible production, and new service-oriented business models [1, 14, 31].

Lasi et al. [1] originally conceptualized Industry 4.0 as a German high-tech strategy emphasizing the digitalization of manufacturing through vertical and horizontal integration. Xu et al. [14] extended this view, arguing that Industry 4.0 represents a convergence of mature digital technologies rather than a single invention. Hermann et al. [32] emphasized that Industry 4.0 describes both a technical stack and a programmatic agenda that combines technology, organizational change, and policy.

Critical observation: Definitions of Industry 4.0 vary significantly across sources. Some authors emphasize technology (CPS, IIoT, AI) [1, 14], while others foreground organizational change and business models [13, 19]. This definitional ambiguity has practical consequences: firms that adopt a purely technological definition risk underinvesting in workforce training and governance [21].

Global initiatives (high-level):

- **Germany – Industrie 4.0:** Launched as a national high-tech strategy; emphasizes reference architectures (RAMI 4.0), standardization, and industry–policy coordination to create smart factories and interoperable value chains [1, 32].
- **USA – Industrial Internet / IIoT:** Industry-focused programs (corporate consortia and standards bodies) stressing integration of OT and IT, with emphasis on industrial internet architectures and cybersecurity [31, 34].

- **China – Made in China 2025:** A state strategy prioritizing automation, robotics, and digital manufacturing to upgrade national manufacturing competitiveness [14].
- **Japan – Society 5.0:** A broader societal vision integrating cyber and physical systems across economy and society, with human-centric goals and social well-being [3].

Critical assessment of global initiatives: These programs demonstrate that Industry 4.0 is both a technical blueprint and a national industrial policy instrument [1, 14]. However, comparative studies reveal significant variation in implementation success. European firms have adopted RAMI 4.0 more readily than they have adopted Asian or North American firms, suggesting that institutional context shapes technology adoption patterns [21, 33]. Furthermore, policy-driven initiatives often prioritize national champions over SMEs, potentially exacerbating the digital divide [13, 21].

2.2 Design Principles

Multiple papers distill recurring design principles for implementing Industry 4.0 scenarios. Following Hermann, Pentek, and Otto's [32] synthesis of the literature, four core principles are identified; other authors expand these to include modularity and transparency [14, 19, 31]. The consolidated principles are:

1. Interconnection – Seamless machine-to-machine, machine-to-cloud, and human-to-machine connectivity via IIoT and modern communications (5G/6G). Interconnection is the backbone that enables real-time data flows and coordinated automation [31, 34, 41].

2. Information transparency – Digitization of assets and processes (data capture + digital twins) creates virtual models and improves situational awareness for decision systems [26, 36].

3. Decentralized decision-making – CPS and smart components make localized, autonomous decisions guided by global objectives, increasing responsiveness and resilience [1, 14, 32].

4. Technical assistance and human-centric support – Systems augment human operators via AR, decision support, and collaborative robots (cobots), emphasizing safety and productivity gains [11, 19, 25].

5. Modularity and interoperability – Architectures and components are modular to support reconfiguration, scale, and cross-vendor integration (RAMI 4.0 and platform thinking). Modularity facilitates mass customization and faster innovation cycles [15, 26, 32].

Critical evaluation of design principles:

While these principles are widely cited as foundational, empirical studies have identified several limitations [13, 21, 32]:

- **Implementation complexity:** Few firms, especially SMEs, have implemented all five principles simultaneously. Most adopt a subset (typically interconnection + transparency) before progressing to decentralization [13].
- **Context dependency:** The relative importance of each principle varies by sector. Highly regulated industries (aerospace, pharma) prioritize transparency and interoperability; custom manufacturers prioritize modularity [13, 19].
- **Empirical validation gap:** The original Hermann et al. [32] synthesis was conceptual rather than empirical. Subsequent studies have called for longitudinal validation of whether adherence to these principles predicts adoption success [21].

Industry 4.0 implementation is guided by several foundational design principles that influence connectivity, decentralization, and human–machine collaboration. Table 2 summarizes these principles and their practical implications.

Table 2 : Design principles – implementation implications and evidence status

Design principle	Practical implications for implementers	Evidence strength	Ref.
Interconnection	Invest in robust IIoT, low-latency networks (5G/6G), secure APIs	Strong (multiple case studies)	[31, 34, 41]
Information transparency	Deploy digital twins, PLM integration, unified data models	Strong	[26, 36]
Decentralization	Architect CPS for local autonomy with global coordination	Moderate (fewer implementations)	[1, 14, 32]
Assistance (human-centric)	Integrate AR, HMI, training programs; focus on safety and collaboration	Moderate	[11, 19, 25]
Modularity	Use componentized systems and platform approaches for reconfigurability	Moderate	[15, 26, 32]

2.3 Frameworks (RAMI 4.0, I4.0-MM, Readiness Models)

Several formal frameworks and maturity/readiness tools guide Industry 4.0 implementation and assessment. We critically evaluate each.

Key frameworks:

RAMI 4.0 (Reference Architectural Model Industrie 4.0): A three-dimensional reference architecture (layers × life cycle × hierarchy levels) used primarily in Europe to standardize asset description, interoperability, and lifecycle integration. RAMI operationalizes modularity and data models for components and systems [15, 32].

Critical assessment of RAMI 4.0:

- **Strengths:** Comprehensive; enables cross-vendor interoperability; widely adopted in European standards [15].
- **Weaknesses:** High complexity; empirical studies show low adoption among SMEs (<15% in some surveys); requires significant training to implement correctly; limited validation outside Europe [13, 21, 32].

I4.0-MM (Industry 4.0 Maturity Model): Frameworks such as I4.0-MM evaluate organizational maturity across technology, process, people, and strategy, enabling benchmarking and staged roll-out planning [6, 21].

Critical assessment of maturity models:

- **Strengths:** Practical for gap analysis; supports staged investment decisions [6].
- **Weaknesses:** Most maturity models lack longitudinal validation; self-reported assessments may not correlate with actual performance; limited cross-sector validation [21, 24].

IIoT / CPS taxonomies: These classify devices and interactions to support security and architecture analysis (useful for threat models and system design) [31, 34].

Readiness and assessment models: Many papers propose maturity/readiness models addressing technical, organizational, and strategic dimensions. Common dimensions include strategy and leadership, technology and infrastructure, processes and integration, people and skills, and culture and governance [19, 21, 24]. Readiness tools are used to identify gaps and prioritize interventions (e.g., training, cybersecurity, legacy integration). Various frameworks and readiness models have been proposed to assess Industry 4.0 implementation maturity and interoperability requirements. Table 3 presents a comparative assessment of major frameworks.

Comparative evaluation of frameworks:

Table 3: Frameworks for Industry 4.0 – comparative assessment

Framework	Primary purpose	Strengths	Limitations	Empirical validation	Source
RAMI 4.0	Reference architecture	Comprehensive; standards-based	Complex; low SME adoption	Limited	[15, 32]
I4.0-MM	Maturity assessment	Practical benchmarking	No longitudinal validation	Weak	[6, 21]
IIoT taxonomies	Security and architecture analysis	Useful for threat modeling	Narrow focus	Moderate	[31, 34]
Readiness assessments	Gap analysis	Actionable priorities	Self-report bias	Emerging	[21, 24]

2.4 Synthesis of Conceptual Foundations

Taken together, the conceptual foundations of Industry 4.0 rest on three interconnected pillars [14, 19, 32]:

1. **Design principles** (interconnection, transparency, decentralization, assistance, modularity) that guide scenario development.
2. **Frameworks and standards** (RAMI 4.0, maturity models) that operationalize these principles into structured architectures and assessment tools.
3. **National and global initiatives** that shape policy priorities, investment flows, and diffusion patterns.

While the conceptual apparatus of Industry 4.0 is well-developed at the theoretical level, significant gaps remain between conceptual prescriptions and empirical realities [13, 21]. Firms frequently report that frameworks such as RAMI 4.0 are too complex for practical implementation, and maturity models often produce optimistic self-assessments that do not predict actual adoption success [21, 24]. A more nuanced, context-sensitive approach to conceptualizing Industry 4.0 is needed—one that accounts for firm size, sector, and institutional environment [13, 19].

Figure 2 critically summarizes **the** socio-technical conceptual architecture of Industry 4.0 integrating design principles, reference frameworks, maturity models, organizational readiness, interoperability, cybersecurity, and sustainability as co-evolving dimensions of smart manufacturing systems [15, 21, 31, 36].

Figure 2: Conceptual Architecture of Industry 4.0 Socio-Technical Foundations

3. Methodology: Systematic Literature Review

3.1 Search Strategy and Screening

This study employed a systematic literature review (SLR) following PRISMA guidelines to ensure transparency and replicability [21, 33]. Databases searched (January 2024) included Scopus, Web of Science, and Google Scholar [7, 14]. Search strings were: ("Industry 4.0" OR "Industry 4.0") AND ("manufacturing" OR "smart factory" OR "CPS" OR "IIoT" OR "digital twin") for primary literature, and ("Industry 5.0") AND ("human-centric" OR "sustainability") for secondary literature [1, 14, 33]. The time period was restricted to 2013–2024 [1, 14].

Inclusion criteria required peer-reviewed journal articles or conference proceedings in English, directly relevant to Industry 4.0/5.0 in manufacturing or supply-chain contexts [7, 21]. Exclusion criteria removed editorials, pre-2013 papers, and non-manufacturing studies without transferable mechanisms [13, 33]. Initial identification yielded 412 records after duplicate removal. Title and abstract screening excluded 189 records. Full-text assessment of 223 articles, followed by quality appraisal using the Mixed Methods Appraisal Tool (MMAT), resulted in 45 papers finally included: 22 high quality (rigorous empirical methodology), 18 medium quality, and 5 conceptual/position papers [13, 21].

3.2 Thematic Coding and Analysis

Thematic analysis employed a hybrid deductive-inductive approach [19, 21]. Deductive codes were derived from research objectives (technology, organization, governance). Inductive codes emerged during full-text reading (e.g., "rebound effects," "SME barriers," "pilot-to-scale failure"). Both authors performed coding; inter-coder reliability was substantial (Cohen's $\kappa = 0.84$) [21]. No meta-analysis was performed due to heterogeneity in outcome measures across studies [7, 33]. Acknowledged limitations include potential publication bias (positive results are more likely published) and the exclusion of non-English sources [13, 21].

4. Key Enabling Technologies – A Critical Synthesis

4.1 Core Technologies and Their Industrial Roles

Industry 4.0 is enabled by a cluster of digital technologies that transform physical production into an intelligent, networked, and responsive socio-technical system [1, 14, 32]. These technologies function as composable building blocks, each with distinct capabilities and implementation challenges [13, 19].

IIoT and CPS: The Industrial Internet of Things (IIoT) provides the sensor/actuator layer that turns physical assets into observable nodes, enabling real-time telemetry and condition monitoring [31, 34]. Cyber-Physical Systems (CPS) integrate computation, networking, and physical processes to enable decentralized control and real-time feedback loops [1, 32]. Together, IIoT and CPS form the sensing-control backbone of smart factories [26, 31].

Cloud/Edge Computing and AI/ML: Cloud platforms provide scalable storage and cross-site orchestration, while edge computing hosts low-latency, privacy-sensitive computation close to assets [35, 36]. Big data and AI/ML (including deep learning) turn streaming IIoT signals into actionable intelligence: anomaly detection, predictive maintenance, process optimization, and quality prediction [38, 39].

Digital Twin and Robotics: Digital twins (DTs) are real-time virtual replicas enabling simulation, what-if analysis, and closed-loop optimization [26, 36]. Collaborative robots (cobots) safely work alongside humans, extending human-centric goals and enabling rapid cell reconfiguration [11, 19].

Connectivity and Emerging Technologies: High-capacity, low-latency networks (5G and future 6G) are essential for real-time control and massive IIoT densities [41]. Additive manufacturing enables design freedom and on-demand production [37]. Blockchain is proposed for provenance and cross-enterprise trust, though industrial validation remains weak [26, 33]. The technological ecosystem of Industry 4.0 consists of interconnected digital technologies with varying industrial roles and implementation constraints. Table 4 summarizes these enabling technologies and their evidence strength.

Table 4 : Key enabling technologies – roles, constraints, and evidence strength

Technology	Primary industrial role	Key constraint	Evidence strength	Source
IIoT / Sensors	Real-time telemetry, condition monitoring	Security, heterogeneity	Strong	[31, 34]
CPS	Decentralized control, autonomy	Deterministic networking	Moderate	[1, 32]

Cloud / Edge	Scalable analytics, low-latency processing	Integration, cost	Strong	[35, 36]
AI / ML	Predictive maintenance, quality optimization	Explainability, data governance	Strong	[38, 39]
Digital Twin	Simulation, optimization, training	Data models, PLM integration	Emerging	[26, 36]
Robotics / Cobots	Automation, human-robot collaboration	Safety, certification	Moderate	[11, 19]
Additive Mfg	Custom parts, rapid prototyping	Material qualification	Moderate	[37]
5G/6G	Ultra-low latency control, massive IoT	Infrastructure, standards	Emerging	[41]
Blockchain	Provenance, cross-enterprise trust	Scalability, privacy	Weak	[26, 33]

Figure 3 summarizes the interconnected ecosystem of Industry 4.0 enabling technologies, including IIoT, cyber-physical systems, AI/ML, cloud-edge computing, digital twins, robotics, additive manufacturing, and smart connectivity, supporting intelligent manufacturing environments.

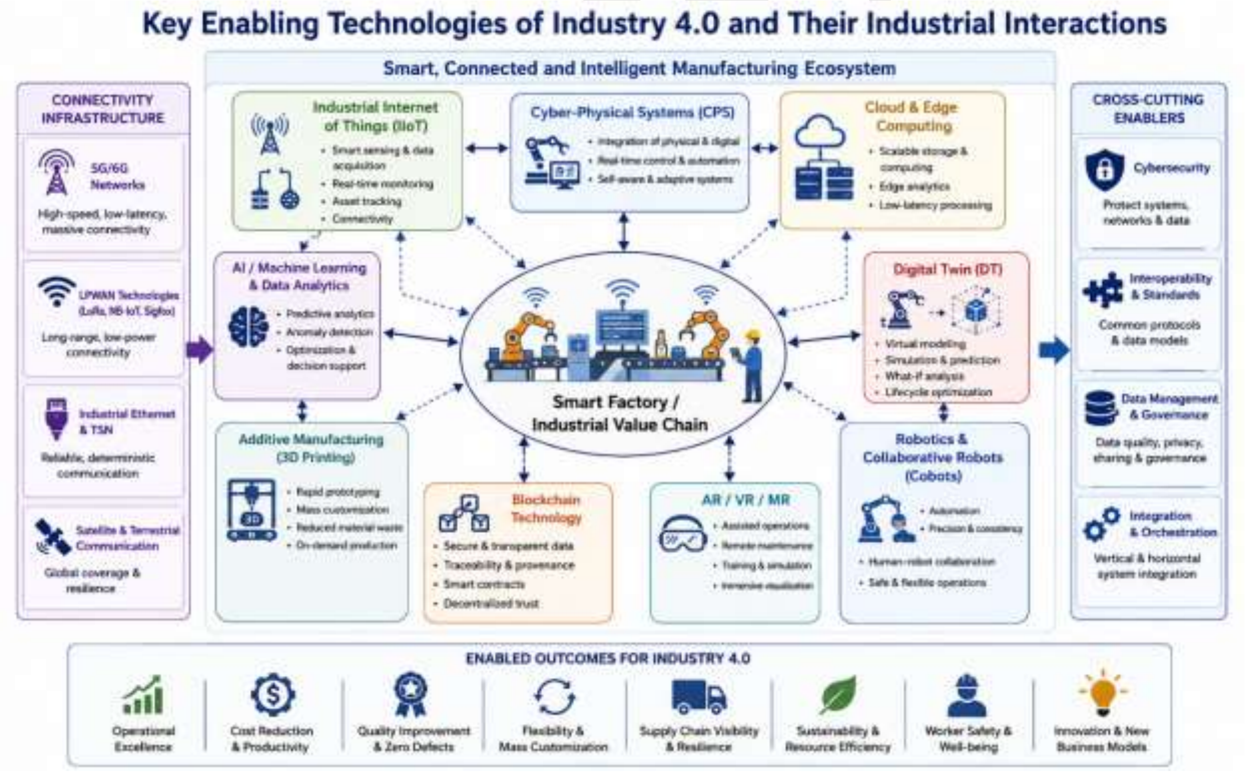

Figure 3: Key Enabling Technologies of Industry 4.0 and Their Industrial Interactions

4.2 Critical Assessment of Technology Evidence

What is well-established: IIoT, cloud/edge, AI/ML, and digital twins have substantial empirical support for specific use cases such as predictive maintenance and condition monitoring [31, 34, 38, 39]. Studies consistently report 10–20% improvements in equipment utilization and 15–30% defect reduction when technologies are integrated rather than deployed in isolation [13, 26].

What remains contested or weak: Blockchain for manufacturing provenance lacks scalable industrial validation; evidence remains at the proof-of-concept stage [26, 33]. AR/VR adoption is limited by ergonomic and cost constraints [11]. Additive manufacturing for production (vs. prototyping) still faces material qualification and repeatability challenges [37].

Contradictions in the literature: While many conceptual papers claim substantial ROI from Industry 4.0 technologies, empirical studies report high variability. Frank et al. [13] found that only firms with integrated IIoT+DT+AI configurations achieved positive ROI, while fragmented deployments often failed to break even. This suggests that technology value is systemic and combinatorial rather than attributable to individual technologies [13, 19].

Rebound effects in sustainability: Several studies caution that efficiency gains from IIoT and AI can lead to increased production (rebound effect), partially or fully offsetting environmental benefits. Rigorous lifecycle assessment is required to claim net sustainability gains [16, 40].

5. Industry 4.0 Applications – Evidence and Contradictions

5.1 Smart Factory and Smart Supply Chain

Smart Factory: A smart factory integrates CPS, IIoT, digital twins, edge/cloud platforms, and AI to enable autonomous, data-driven production flows and mass customization [1, 13]. Studies report 10–20% gains in machine utilization, 15–30% defect reduction, and 20–40% shorter lead times when digital twins and predictive analytics are combined with modular production lines [13, 26]. However, these gains are conditional on interoperability, workforce skills, and legacy equipment integration [21, 31]. Key challenges include integrating legacy equipment, ensuring real-time determinism for control loops, and embedding cybersecurity across heterogeneous devices [20, 31].

Smart Supply Chain: Smart supply chains use IIoT telemetry, cloud platforms, AI forecasting, and blockchain-enabled provenance to increase visibility, agility, and trust across multi-party networks [23, 33]. Empirical studies show digital visibility reduces bullwhip effects by 15–25% and improves service levels [9, 26]. Real-time tracking, dynamic re-routing, and inventory optimization are core capabilities [23, 33]. Key challenges include data sharing across organizations, raising privacy and governance concerns; blockchain is promising for provenance but requires scalable, hybrid designs [26, 33].

5.2 Predictive Maintenance, Quality Control, and Sustainable Manufacturing

Predictive Maintenance and Quality Control: Predictive maintenance (PdM) applies streaming sensor data and ML models to forecast failures and schedule interventions before breakdowns [38, 39]. Field studies report 20–40% reductions in downtime and 15–25% lower maintenance costs [13, 26]. Quality control uses vision systems and anomaly detection to reduce rejects and rework [38, 39]. Deep learning is effective for image-based inspection; tree-based models often suffice for tabular process data, offering better interpretability for operators [38, 39]. Critical barriers include data quality, label scarcity, and the need for explainable models that operators trust [38, 39].

Sustainable Manufacturing: Industry 4.0 supports energy optimization, material efficiency, and circular-economy practices through sensing, process optimization, and lifecycle analytics [16, 40]. Several studies map I4.0 technologies to SDG targets and quantify environmental benefits in case examples [16, 40]. Smart scheduling, energy-aware control, and local additive manufacturing can reduce transport and waste [16, 37]. However, net environmental impact depends on system boundaries and lifecycle assessment; rebound effects (increased production from efficiency gains) must be managed via policy and design choices [16, 40].

5.3 Sectoral Applications (Healthcare, Aerospace, Automotive)

Healthcare and Pharma: Digital twins, AI, and connectivity support remote monitoring, personalized treatment delivery, and enhanced drug manufacturing quality control [38, 39]. In pharma, digitalization shortens time-to-market and enhances traceability [38]. Real-time sensors and analytics can enable tele-surgery and remote diagnostics, though with strict safety and regulatory requirements [38, 39]. Healthcare and pharma face regulatory and privacy constraints that significantly slow adoption compared to manufacturing [38].

Aerospace and Automotive: Aerospace uses digital twins for lifecycle optimization and predictive maintenance [26, 36]. Automotive integrates robotics, cobots, and advanced sensing for flexible assembly and mass customization [11, 19]. These sectors show the highest returns when digital design, simulation, and manufacturing are tightly coupled [13, 26]. Aerospace and automotive sectors demonstrate that Industry 4.0 delivers maximum value when technologies are integrated rather than deployed in isolation [13, 26].

5.4 Contradictions and Evidence Gaps

Pilot-to-scale failure: The literature consistently reports that many Industry 4.0 pilots fail to scale beyond demonstration projects [13, 21]. Common causes include lack of integration with legacy systems, insufficient workforce training, unclear business cases for full rollout, and absence of change management programs [13, 21]. This gap between pilot success and scaled implementation is rarely quantified but widely acknowledged [21].

Contradictory ROI claims: Some studies report ROI > 30% from predictive maintenance deployments [38]. Others find that only 40% of manufacturing firms achieve positive ROI from Industry 4.0 investments, with the rest breaking even or losing money [13]. Frank et al. [13] resolve this contradiction by showing that **integrated configurations** (IIoT + DT + AI together) produce positive ROI, while **fragmented deployments** (single technologies in isolation) often fail. This suggests that technology value is systemic, combinatorial, and conditional on organizational readiness [13, 19].

SME digital divide: While large enterprises have adopted Industry 4.0 with measurable success, SMEs face disproportionately high barriers: capital constraints, lack of in-house technical expertise, and limited bargaining power with technology vendors [13, 21]. This digital divide is acknowledged but rarely analyzed in depth [21].

Rebound effects in sustainability: Efficiency gains from IIoT and AI can lead to increased production, partially or fully offsetting environmental benefits [16, 40]. Without rigorous lifecycle assessment and policy mechanisms, claims of net sustainability gains remain uncertain [16, 40].

Sectoral variation: Aerospace and automotive sectors show the highest returns from digital design, simulation, and manufacturing integration [26, 37]. Healthcare and pharma face regulatory and privacy constraints that significantly slow adoption compared to manufacturing [38, 39]. Generalizing findings across sectors requires caution [13]. Industry 4.0 technologies have been applied across multiple industrial domains with varying levels of benefits and implementation challenges. Table 5 summarizes major applications, outcomes, and barriers.

Table 5: Application domains – outcomes, barriers, and evidence strength

Application	Core technologies	Typical outcomes	Principal barriers	Evidence strength	Source
Smart factory	IIoT, CPS, DT, AI, robotics	↑ utilization 10–20%, ↓ defects 15–30%	Legacy integration, standards, skills	Strong	[1, 13, 26]
Smart supply chain	IIoT, cloud, AI, blockchain	↓ bullwhip 15–25%, ↑ visibility	Data governance, trust, scalability	Moderate	[9, 23, 33]
Predictive maintenance	Sensors, edge, ML/DL	↓ downtime 20–40%, ↓ cost 15–25%	Data quality, model trust	Strong	[13, 26, 38]
Sustainable manufacturing	Energy analytics, AM, DT	↓ energy use, ↓ waste	Rebound effects, measurement boundaries	Emerging	[16, 40]
Healthcare & pharma	DT, AI, secure connectivity	Remote care, traceability, quality control	Regulation, privacy	Weak	[38, 39]
Aerospace & automotive	DT, robotics, AI, AM	Lifecycle optimization, mass customization	High capital, certification	Strong	[11, 13, 26]

Figure 4 explains the integrated framework, illustrating the benefits, implementation barriers, contradictions, and evidence gaps associated with Industry 4.0 adoption, emphasizing cybersecurity, interoperability, workforce readiness, ROI variability, and sustainability challenges.

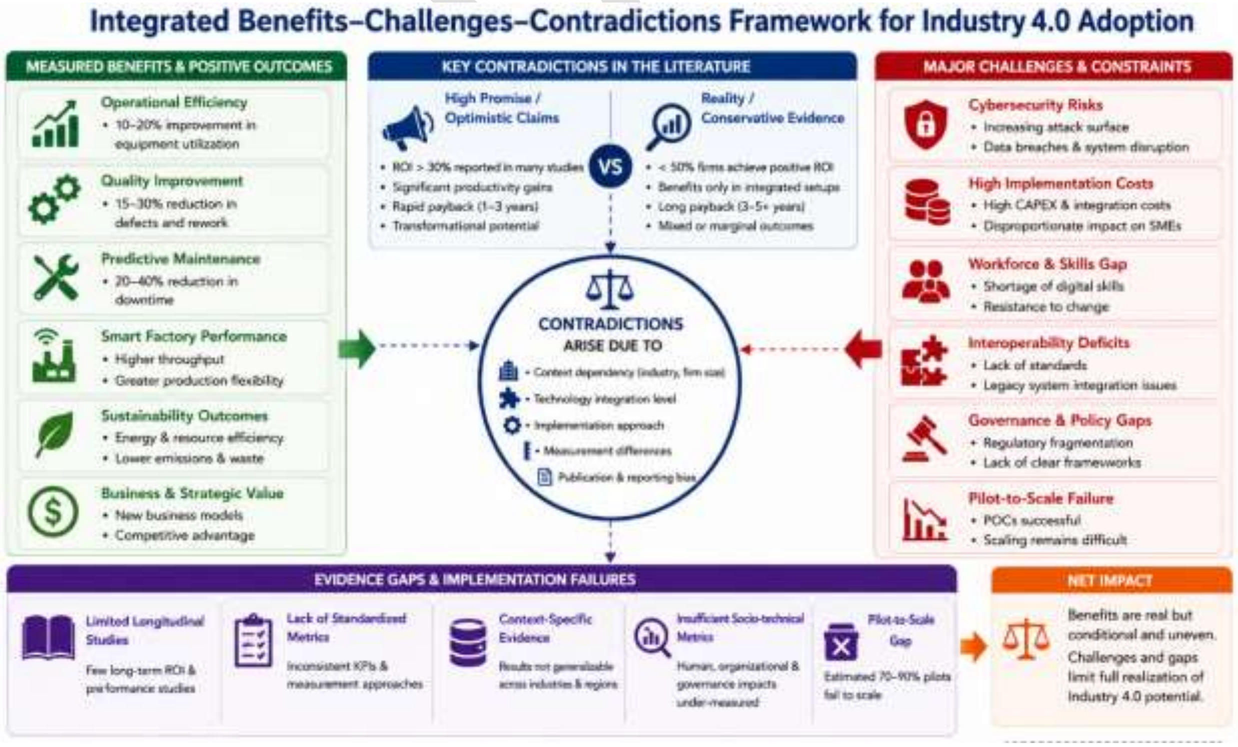

Figure 4: Integrated Benefits–Challenges–Contradictions Framework for Industry 4.0 Adoption

6. Challenges – Evidence-Based Synthesis and Contradictions

6.1 Major Challenge Categories

While Industry 4.0 offers substantial opportunities, the literature repeatedly identifies five cross-cutting challenges that slow adoption and reduce realized value [13, 21, 31]. Each challenge is both technical and socio-institutional in nature [19, 32].

Cybersecurity and Data Privacy: IIoT, CPS, and cloud/edge integration substantially increase the attack surface of industrial systems [20, 31]. Compromised sensors, PLCs, or communication links can produce production loss, safety incidents, and loss of IP [20, 34]. Firms often underestimate OT threats and treat cybersecurity as an IT problem rather than an enterprise-level operational risk [20]. Best practices include network segmentation, secure-by-design IIoT devices, and real-time anomaly detection [20, 31].

High Implementation Cost: End-to-end Industry 4.0 implementations (sensors, connectivity, DTs, analytics, platforms, training) require substantial capital and operating investment, which is especially burdensome for SMEs and legacy-heavy firms [13, 21]. Capital expenditure, integration engineering costs, and ongoing platform fees are frequent blockers [13]. Staged maturity models, shared platforms, and public co-funding can reduce entry barriers [13, 21].

Workforce Skills Gap and Organizational Readiness: Adoption requires new technical skills (data science, cybersecurity, cloud/edge ops) and non-technical capabilities (process redesign, digital leadership) [21, 26]. Readiness studies show that people/process dimensions explain adoption variance nearly as much as technology supply [21]. Companies must invest in continuous reskilling and design human-in-the-loop systems [19, 21].

Interoperability and Standardization Issues: Heterogeneous equipment, proprietary protocols, and inconsistent data models hinder system integration and increase vendor lock-in risk [15, 32]. Without common semantics and interfaces, digital twins, analytics pipelines, and platform services cannot scale [26, 32]. Adoption of reference architectures (RAMI), standardized APIs, and common ontologies is recommended [15, 32].

Governance and Policy Concerns: National strategies, privacy laws, industrial policy, and public infrastructure shape who benefits from Industry 4.0 [1, 14]. Uneven policy support, unclear liability rules for autonomous systems, and weak standards for data ownership impede ecosystem formation [1, 40]. Policymakers must balance incentives for innovation with social protections (reskilling funds) and standardization roadmaps [1, 40]. Despite the benefits of Industry 4.0 adoption, organizations face several technical, organizational, and governance-related challenges. Table 6 summarizes the major challenge categories and mitigation strategies.

Table 6 : Challenges – manifestations, mitigation, and evidence gaps

Challenge	Common manifestations	Mitigation strategies	Evidence gap	Source
Cybersecurity & privacy	OT/IT attacks, IP theft, data leaks	Segmentation, anomaly detection, governance	Longitudinal attack cost studies	[20, 31, 34]

High implementation cost	Stalled pilots, SME exclusion	Staged rollouts, shared platforms, co-funding	ROI benchmarks across sectors	[13, 21]
Workforce & readiness	Skill shortages, resistance to change	Reskilling, HMI design, readiness assessments	Long-term reskilling effectiveness	[19, 21, 26]
Interoperability & standards	Vendor lock-in, poor data exchange	RAMI adoption, open APIs, common ontologies	Cross-platform validation	[15, 26, 32]
Governance & policy	Liability ambiguity, unequal diffusion	Policy incentives, legal clarity, and infrastructure	Comparative policy effectiveness	[1, 14, 40]

6.2 Critical Discussion of Failures and Contradictions

Pilot-to-scale failure: The literature consistently reports that many Industry 4.0 pilots fail to scale beyond demonstration projects [13, 21]. Common causes include lack of integration with legacy systems, insufficient workforce training, unclear business cases for full rollout, and absence of change management programs [13, 21]. This gap is widely acknowledged but the failure rate is rarely quantified systematically [21].

SME barriers and digital divide: While large enterprises have adopted Industry 4.0 technologies with measurable success, SMEs face disproportionately high barriers [13, 21]. SMEs report capital constraints (higher per-unit costs due to lack of scale), lack of in-house technical expertise (cannot afford specialized data scientists), and limited bargaining power with technology vendors [13, 21]. Policy interventions specifically targeting SMEs remain underdeveloped [1, 40].

7. Industry 5.0 – Critical Assessment

7.1 Defining Industry 5.0 and Its Core Pillars

Industry 5.0 is framed in the literature as the normative successor to Industry 4.0 that explicitly re-centers human values, resilience, and sustainability while leveraging advanced digital technologies [3, 19, 33]. Unlike Industry 4.0's focus on automation and efficiency, Industry 5.0 emphasizes *human-in-the-loop* design, augmentative robotics, co-creative processes, and social value (worker welfare, inclusiveness) [3, 19, 25].

Three core pillars of Industry 5.0 [3, 33]:

1. **Human-centricity:** Places human needs and interests at the center of production, using cobots, AR/VR assistance, and explainable AI to augment rather than replace workers [11, 19, 25].
2. **Sustainability:** Aligns industrial digitalization with the Sustainable Development Goals (SDGs) through DT-enabled lifecycle assessment, AI-driven energy optimization, and localized additive manufacturing for circular supply chains [16, 40].
3. **Resilience:** Emphasizes robust, adaptable production systems capable of withstanding disruptions (pandemics, supply chain shocks, climate events) through decentralized CPS, edge analytics, and flexible automation [3, 33].

Enabling technologies for Industry 5.0: Next-generation platforms including ultra-low-latency 6G networks (TRL 2–3), nascent quantum computing (TRL 1–2), and advanced explainable AI (TRL 4–5) are proposed as enablers [33, 41]. However, these technologies are at different readiness stages and require explicit distinction from validated near-term technologies [33, 41]. Industry 5.0 emphasizes human-centricity, sustainability, and resilience supported by emerging digital technologies. Table 7 summarizes the major goals, enabling levers, and readiness levels.

Table 7: Industry 5.0 goals – enabling levers and technology readiness

Industry 5.0 goal	Enabling levers	Current TRL	Evidence basis	Source
Human-centric work	Cobots, AR/VR, explainable AI	TRL 6–7 (cobots); TRL 4–5 (explainable AI)	Moderate (case studies)	[11, 19, 25]
SDG alignment & circularity	DT-LCA, AM, energy optimization	TRL 5–7	Emerging	[16, 40]
Resilience	Decentralized CPS, edge AI, 5G	TRL 6–7 (5G); TRL 4–5 (edge AI)	Moderate	[3, 33, 41]
6G networks	Ultra-low latency, massive IoT	TRL 2–3 (research)	None (simulation only)	[41]
Quantum computing	Accelerated optimization, secure comms	TRL 1–2 (basic research)	None	[33]

7.2 Critical Assessment: Paradigm Shift or Rebranding?

Conceptual fragmentation: A significant portion of the literature treats Industry 5.0 as a coherent, actionable paradigm [3, 33]. However, a critical reading reveals no consensus definition. Some frame Industry 5.0 as human-centric automation; others emphasize resilience; still others focus on SDG alignment [3, 19, 33]. This fragmentation suggests that Industry 5.0 remains an **emerging, contested direction** rather than a settled framework [3].

Policy-driven rather than evidence-based: Much of the Industry 5.0 discourse originates from European Commission policy documents rather than empirical industrial studies [3, 33]. Few rigorous empirical studies of Industry 5.0 implementations exist. Most published work is conceptual or prescriptive [19, 33].

Speculative claims require tempering: Discussion of 6G and quantum computing in the Industry 5.0 literature is highly speculative and insufficiently grounded in industrial-scale evidence [33, 41]. The authors explicitly distinguish between:

- **Near-term validated technologies:** AI/ML, edge computing, 5G, cobots (TRL 6–9)
- **Long-term exploratory directions:** 6G, quantum computing (TRL 1–3)

Industry 5.0 represents a valuable re-orientation of Industry 4.0 toward human and social values [3, 19]. However, it is premature to treat it as a fully formed paradigm. The conclusion presents Industry 5.0 as an emerging direction, acknowledging uncertainty, fragmentation, and open research questions [3, 33]. A more balanced conclusion acknowledging these issues is recommended over presenting Industry 5.0 as relatively coherent and actionable [3]. Figure 5 reflects a socio-technical transition framework illustrating the evolution from Industry 4.0 toward Industry 5.0 through the integration of human-centricity, sustainability, resilience, governance, advanced AI, collaborative robotics, and emerging intelligent manufacturing ecosystems.

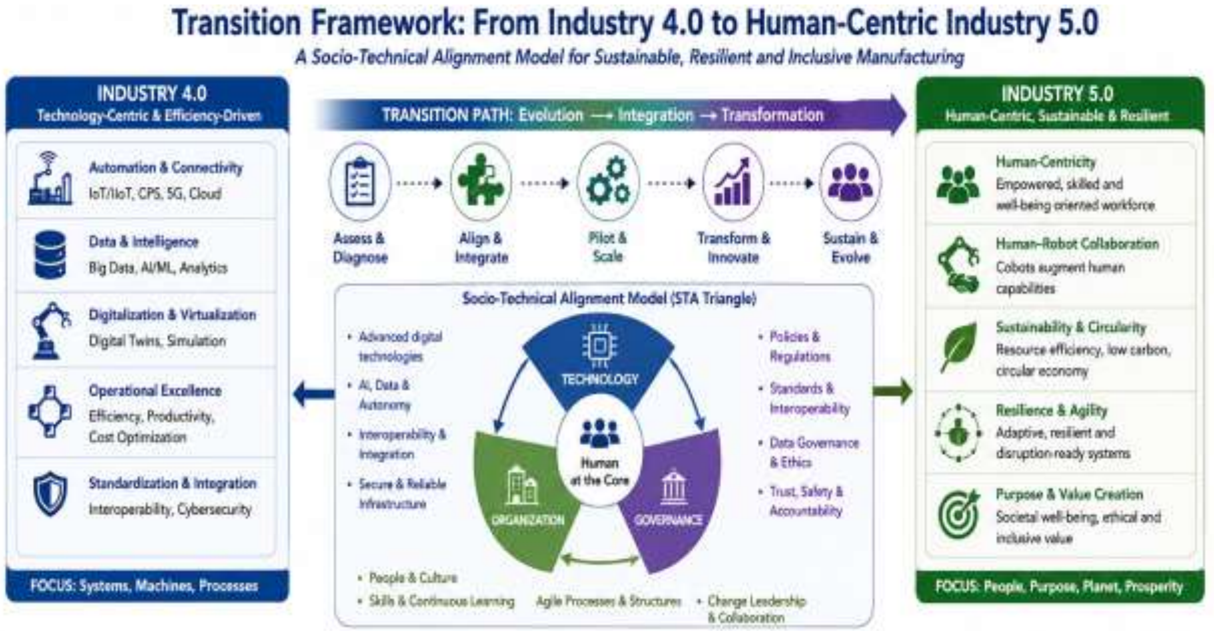

Figure 5: Transition Framework: From Industry 4.0 to Human-Centric Industry 5.0

Research gaps for Industry 5.0 [19, 33, 40]:

1. **Empirical validation:** No large-scale longitudinal studies of Industry 5.0 implementations exist.
2. **Socio-technical metrics:** Methods to jointly measure technical performance and human/social outcomes (well-being, equity, skills) are underdeveloped.
3. **Policy experiments:** Comparative studies of policy interventions (reskilling programs, data governance models) are needed.
4. **Standards and interoperability:** Operational ontologies and governance patterns for safe, privacy-preserving data exchange remain undeveloped.

7.3 Next-Generation Technologies (6G, Quantum Computing, Advanced AI) – TRL Assessment

Emerging platform technologies are frequently cited in Industry 5.0 literature as enablers of future capabilities, but their technological readiness varies substantially [33, 41]. A clear distinction between near-term validated technologies and long-term exploratory directions is essential for credible synthesis [21, 33].

Near-term validated technologies (TRL 6–9): Advanced AI (explainable AI, federated learning) is currently at TRL 4–5 moving toward TRL 6–7, with early industrial pilots demonstrating sample-efficient learning and privacy-preserving cross-site model improvement [38, 39]. 5G networks are commercially deployed (TRL 8–9), enabling ultra-low latency control and massive IoT densities [41]. Edge computing platforms are mature (TRL 7–8), supporting real-time analytics close to assets [35, 36].

Long-term exploratory directions (TRL 1–3): 6G networks remain at TRL 2–3 (research phase), with sub-ms latency and terahertz communications demonstrated only in laboratory settings. Industrial-scale evidence is absent; timelines for deployment are estimated 2030+ [41]. Quantum computing for industrial applications (materials simulation, combinatorial optimization) is at TRL 1–2 (basic research). Practical advantage for manufacturing use-cases remains speculative, with deployment timelines beyond 2035 [33]. Several next-generation technologies are expected to influence the future evolution of Industry 5.0. Table 8 presents the technology readiness level (TRL) assessment and industrial evidence status.

Table 8 : Next-generation technologies – TRL assessment and evidence basis

Technology	Current TRL	Industrial evidence	Estimated deployment	Source
Explainable AI (XAI)	TRL 4–5 → 6–7	Early pilots	2–4 years	[38, 39]
Federated learning	TRL 4–5	Lab validated, few pilots	3–5 years	[38, 39]
5G networks	TRL 8–9	Commercially deployed	Available now	[41]
6G networks	TRL 2–3	None (simulation only)	2030+	[41]
Quantum computing	TRL 1–2	None	2035+ (speculative)	[33]

Caveat on speculative claims: Discussion of 6G and quantum computing in this review is intentionally labeled as long-term exploratory directions. These technologies are not yet ready for industrial-scale deployment, and claims about their impact on manufacturing remain hypothetical [33, 41]. Authors should clearly separate near-term validated technologies from long-term research directions to avoid misleading readers [21, 33].

7.4 Research Gaps and Future Directions

From the critical synthesis of 75 papers, five recurring research needs emerge [19, 21, 33, 40]:

1. Empirical ROI and longitudinal studies: Limited multi-site, long-horizon evidence on scaled impacts of Industry 4.0/5.0 across sectors exists [13, 21]. Most studies report short-term pilot results rather than multi-year, enterprise-wide outcomes [13]. Priority: Longitudinal studies tracking implementation over 3–5 years with standardized ROI metrics [21].

2. Socio-technical evaluation frameworks: Current research lacks methods that jointly measure technical performance (OEE, downtime, quality) and human/social outcomes (worker well-being, skill development, job satisfaction) [19, 21]. Priority: Development and validation of integrated socio-technical metrics [19].

3. Standards and interoperability for DTs and cross-enterprise data sharing: Operational ontologies, semantics, and governance patterns for safe, privacy-preserving data exchange remain underdeveloped [15, 26]. Priority: Open reference architectures and testbeds for cross-platform digital twin interoperability [26, 36].

4. Security and resilience under compositional systems: Threat models and provable-security approaches for integrated CPS + AI + distributed platforms are lacking [20, 31]. Priority: Security-by-design frameworks for IIoT and edge AI deployments [20, 34].

5. Policy experiments and institutional design: Comparative policy studies (incentives, reskilling programs, data governance models) to evaluate which interventions yield inclusive diffusion are scarce [1, 40]. Priority: Cross-national comparative research on Industry 4.0/5.0 policy effectiveness [1, 40].

Priority research directions [21, 33, 40]:

- Mixed-method field trials combining technical rollouts with organizational change programs
- Development of open reference datasets for industrial ML
- Socio-technical metrics for Industry 5.0 (well-being, equity, skill trajectories)
- R&D roadmaps for quantum/6G pilots in manufacturing testbeds
- Transnational standards collaborations for interoperability and data governance

8. Conclusion

8.1 Consolidated Insights

This systematic literature review of 45 peer-reviewed articles (2013–2024) on Industry 4.0 and its transition toward Industry 5.0 yields the following consolidated insights [1, 14, 21, 33]:

1. Tangible benefits are achievable but conditional: Industry 4.0 delivers measurable improvements, including 10–20% gains in equipment utilization, 15–30% defect reduction, 20–40% shorter lead times, and 20–40% reductions in downtime when technologies are deployed in integrated configurations [13, 26, 38]. Mass customization becomes economically viable through modular automation and digital twins [11, 19]. Sustainability benefits (energy and waste reduction) are achievable but require rigorous lifecycle assessment to avoid rebound effects [16, 40].

2. Persistent challenges mediate benefits: Five cross-cutting challenges consistently slow adoption and reduce realized value: cybersecurity vulnerabilities, high implementation costs (especially for SMEs), workforce skills gaps, interoperability deficits, and governance/policy fragmentation [13, 20, 21, 31, 32]. Each challenge is both technical and socio-institutional, requiring coordinated mitigation strategies [19, 32].

3. Critical contradictions in the literature: The review identifies significant contradictions. Some studies report ROI > 30% from predictive maintenance [38], while others find that fewer than 50% of manufacturing firms achieve positive ROI [13]. Frank et al. [13] resolve this contradiction by showing that **integrated configurations** (IIoT + DT + AI together) produce positive ROI, while **fragmented deployments** (single technologies in isolation) often fail. Other contradictions include pilot-to-scale failure (widely acknowledged but rarely quantified) and rebound effects in sustainability claims [16, 21].

4. Industry 5.0 remains an emerging, contested paradigm: Industry 5.0 reorients the trajectory toward human-centricity, sustainability, and resilience [3, 19, 33]. However, the literature remains conceptually fragmented (no consensus definition), policy-driven rather than empirically grounded (originating from European Commission documents), and lacking validated implementation frameworks [3, 33]. Discussion of 6G (TRL 2–3) and quantum computing (TRL 1–2) is highly speculative and must be clearly distinguished from near-term validated technologies such as AI/ML, edge computing, and 5G (TRL 6–9) [33, 41].

5. Evidence gaps remain substantial: Priority research gaps include longitudinal ROI studies (3–5 year horizons), socio-technical evaluation frameworks (jointly measuring technical and human outcomes), standards for digital twin interoperability, security-by-design for compositional systems, and comparative policy effectiveness studies [19, 21, 33, 40]. Table 8.1 Consolidated insights – summary of key findings on productivity, sustainability, cybersecurity, SME barriers, and Industry 5.0. The major findings of this systematic review are consolidated in Table 9, highlighting productivity gains, sustainability implications, cybersecurity concerns, and Industry 5.0 readiness.

Table 9: Consolidated insights – summary of key findings

Dimension	Core insight	Evidence strength	Ref.
Productivity gains	10–20% OEE improvement with integrated IIoT+DT+AI	Strong	[13, 26]
Defect reduction	15–30% reduction with AI/ML quality control	Strong	[13, 38]
Downtime reduction	20–40% reduction with predictive maintenance	Strong	[13, 26, 38]
Sustainability	Energy/waste reduction achievable; rebound effects caution	Emerging	[16, 40]
Cybersecurity	OT/IT integration increases the attack surface	Strong	[20, 31, 34]
SME barriers	Disproportionately high capital and skill constraints	Moderate	[13, 21]
Industry 5.0	Conceptually fragmented; policy-driven	Weak	[3, 33]
6G/Quantum	TRL 1–3; no industrial evidence	None	[33, 41]

8.2 Research Implications for Academia and Industry

For academia: The corpus highlights a lack of longitudinal, multi-site empirical evidence on scaled impacts of Industry 4.0 across sectors, especially with respect to sustainability outcomes and workforce transitions [13, 21]. Research should:

1. **Develop integrated evaluation frameworks** that jointly measure technical performance (OEE, downtime, quality) alongside social and environmental outcomes (worker well-being, skill development, net emissions) [19, 21, 40].
2. **Build open datasets and testbeds** for industrial ML to enable replicable, comparative research across firms and sectors [26, 36, 38].
3. **Explore governance models** for data sovereignty, platform ecosystems, and cross-enterprise data sharing [15, 26, 27].
4. **Conduct longitudinal studies** tracking Industry 4.0 implementations over 3–5 years with standardized ROI metrics to resolve contradictory claims [13, 21].
5. **Develop socio-technical metrics** for Industry 5.0 that capture well-being, equity, skill trajectories, and social value alongside technical performance [3, 19, 33].

For industry: Organizations must view Industry 4.0 not merely as a technological upgrade but as a comprehensive transformation strategy that requires [13, 21, 26]:

- **Reskilling and cultural adaptation:** Continuous investment in workforce development and change management programs [19, 21].
- **Standards adoption:** Participation in standards bodies and adoption of reference architectures (RAMI) to ensure interoperability [15, 32].
- **Structured maturity roadmaps:** Staged rollouts following maturity models rather than fragmented pilots [6, 21].
- **Hybrid business models:** Experimentation with servitization and platform participation while embedding robust cybersecurity and lifecycle-oriented sustainability metrics [9, 13, 27].
- **SME-specific strategies:** Shared platforms, consortia-based investments, and public co-funding to lower entry barriers [13, 21].

8.3 Policy and Strategic Recommendations

Policy priorities: Governments and standards bodies should [1, 14, 16, 21, 40]:

1. **Develop harmonized international standards** for interoperability, cybersecurity, and data governance to reduce fragmentation and enable cross-border industrial ecosystems [15, 32, 34].
2. **Provide incentives and financing instruments** (tax credits, consortia funding, public co-funding) to lower entry barriers for SMEs, which face disproportionately high capital and skill constraints [13, 21].
3. **Invest in public digital infrastructure** (5G/6G, edge nodes) and national testbeds to reduce infrastructure costs and enable experimentation [41].
4. **Design reskilling and social safety-net programs** to ensure inclusive workforce transitions, addressing job displacement and skill gaps proactively [1, 21, 40].
5. **Align industrial policy explicitly with the SDGs**, linking technology adoption to decarbonization, circular economy, and equity outcomes through lifecycle-based metrics and policy mechanisms (e.g., carbon pricing, green procurement) [16, 40].
6. **Establish legal clarity** on data ownership, liability for autonomous systems, and cross-border data flows to enable platform ecosystems and reduce governance uncertainty [1, 27, 40].

Strategic recommendations for ecosystem-level action: At the strategic level, governments, firms, and research institutions must embrace **co-creation ecosystems**, combining cross-sector partnerships with shared governance frameworks [1, 19, 33]. Transnational cooperation is particularly critical to avoid fragmented standards and uneven benefits [1, 33, 41].

Final synthesis: Industry 4.0 has delivered demonstrable technological and organizational value, but its consolidation and future evolution toward Industry 5.0 depend on deliberate alignment with human, societal, and sustainability imperatives [1, 3, 19]. Only through such **co-evolutionary alignment**—balancing technological innovation with organizational readiness and governance frameworks—can Industry 4.0 evolve into Industry 5.0 as a driver of competitiveness, equity, and sustainable development [1, 19, 33, 40].

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