

Review Article

Industrial Engineering in the Age of Industry 5.0: Bridging Technology, Humanity, and Sustainability

Aryaveer Patel¹, Priyam Parikh^{2,*} , Parth Atulkumar Shah² 

¹Higher Secondary Department, Ahmedabad International School, Ahmedabad, India

²Product Design Department, Anant National University, Ahmedabad, India

Abstract

The transition from Industry 4.0 to Industry 5.0 marks a paradigm shift from automation and digitalization toward a human-centric, sustainable, and resilient industrial ecosystem. This review paper explores the evolving role of *Industrial Engineering (IE)* within the framework of *Industry 5.0*, emphasizing the integration of advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), robotics, digital twins, and additive manufacturing with human intelligence and creativity. Unlike its predecessor, which primarily focused on efficiency and productivity through automation, Industry 5.0 aims to *restore the human touch in manufacturing*, ensuring that technology augments not replaces human capabilities. The paper synthesizes recent scholarly contributions and industrial case studies to identify how Industry 5.0 redefines traditional IE domains including *operations optimization, production planning, quality control, ergonomics, and supply chain management*. Furthermore, it discusses the alignment of Industry 5.0 with global sustainability goals, circular economy principles, and socio-technical resilience. The review highlights how Industrial Engineers act as key enablers in designing *human-machine symbiotic systems*, optimizing smart factories, and ensuring ethical and sustainable deployment of emerging technologies. Finally, the paper outlines research gaps and future directions, advocating for interdisciplinary frameworks that combine *engineering, data science, and human factors* to achieve a more inclusive and adaptive industrial future. By bridging technology with humanity, Industry 5.0 offers Industrial Engineering a renewed relevance in shaping the factories of tomorrow intelligent, empathetic, and sustainable.

Keywords

Industry 5.0, Industrial Engineering, Human-Machine Collaboration, Sustainable Manufacturing, Smart Factories, Digital Twins

1. Introduction

In recent years, the industrial domain has undergone tremendous transformation under the banner of *Industry 4.0*, leveraging cyber-physical systems, Internet of Things, big data analytics, cloud/edge computing, autonomous control, and smart factories to maximize efficiency, flexibility, and

connectivity. Yet this wave of digitalization, though powerful, exposed significant tensions and limitations: industrial systems optimized for throughput and automation often neglected the well-being of human workers, generated externalities in waste, energy, and social equity, and proved brittle

*Corresponding author: priyam.parikh@anu.edu (Priyam Parikh)

Received: 8 October 2025; **Accepted:** 22 October 2025; **Published:** 19 December 2025



Copyright: © The Author(s), 2025. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

when confronted with systemic shocks such as pandemics, supply chain disruptions, or geopolitical instabilities. Against this backdrop, the emergent concept of *Industry 5.0* is gaining traction as a complementary evolution not a wholesale replacement that strives to reposition the *human*, sustainability, and resilience at the heart of industrial systems [4]. In this conception, Industry 5.0 demands a shift from solely automating tasks toward *cooperative, symbiotic human-machine collaboration*, where intelligent systems augment and empower human creativity, autonomy, and agency [8, 10, 11]. It foregrounds *human-centricity, circular economy, and system resilience* as primary design values rather than secondary constraints, and thereby opens a new frontier for research in industrial engineering and systems design. The European Commission's policy framing, "Industry 5.0: Towards more sustainable, resilient and human-centric industry," has catalysed interest across academia and industry by articulating a vision where production respects planetary boundaries, societal well-being, and worker dignity [17]. Conceptual reviews and content-centric analyses show that while some view Industry 5.0 as an evolutionary extension of Industry 4.0, others treat it as a paradigm shift oriented around socio-technical values [11]. The ambiguity around its precise definition is evident: some scholars emphasize the centrality of human-centred design and empowerment [10], others stress the balanced integration of sustainability, resilience, and human dimensions [7]. A recent architectural design effort in the literature seeks to map the interplay between enabling technologies, design principles, system components, and value outcomes in a holistic Industry 5.0 construct [11]. At the conceptual core, Industry 5.0 is posited to be a *socio-technical phenomenon* in which the evolution of technology is guided by human and environmental priorities, rather than technology driving social change unaccounted [11]. In this light, enabling technologies such as *human digital twins (HDTs)* have drawn deep interest as mechanisms to model, simulate, and enhance human-machine interaction in manufacturing contexts [2]. HDTs promise to incorporate human behavioural, cognitive, and physiological parameters into dynamic models, allowing digital systems to anticipate and adapt to human states and preferences, thereby sustaining collaborative performance. In parallel, *explainable AI, collaborative robotics (cobots), augmented/virtual reality interfaces, edge intelligence, and 5G/6G connectivity* form the technological substrate upon which this human-centric interplay is realized [8, 15]. Recent survey work systematically reviews the panoply of enabling technologies and identifies how each contributes to the tripartite goals of human-centricity, resilience, and sustainability [8]. In applying those ideas to industrial engineering, the challenge becomes one of redesigning models, methods, and systems under *multi-objective constraints* that include human comfort, fatigue, trust, resilience margins, and environmental costs not just throughput or cost minimization. The human-centric pillar contends with real tensions: in transitioning from automation to shared control, issues of trust,

safety, cognitive load, accountability, and potential job displacement anxiety arise. A recent investigation characterizes these *human-centric tensions* in manufacturing contexts, and proposes resolution strategies such as participatory design, adaptive interface design, and progressive automation [12]. Industrial engineering must therefore evolve its core competencies traditionally focused on process optimization, resource allocation, scheduling, and ergonomics to integrate *human models, dynamic adaptability, and circular resource flows*. For example, production planning models need to be reconfigured to support re-configurability and adaptability to disruptions while respecting human workload constraints. Digital twins of production systems must incorporate human behavioural models and real-time feedback loops to enable "what-if" scenario planning. Quality assurance and predictive maintenance systems must consider human error, fatigue-induced variations, and sensor fusion across modalities. Supply chain models must now consider reverse logistics, resource circularity, and resilience in face of external shocks. Workforce planning must include reskilling, human psychological welfare, and training systems (e.g. AR/VR-based training) tailored to evolving roles. Ethical design and governance become integral concerns: industrial engineers must define measurement metrics, accountability protocols, and stakeholder inclusion frameworks that reconcile efficiency with equity and sustainability. Several works emphasize that the human factor the worker's well-being, dignity, autonomy should no longer be a downstream design afterthought, but be core to system architecture and decision-making [10, 11]. However, major *gaps* remain. There is still no universally accepted definition or scope of Industry 5.0; the literature often diverges on how deep sustainability or social goals are embedded [11]. Large-scale industrial case studies are scarce, and most existing work remains at the conceptual or pilot level, lacking empirical validation in real-world settings. Quantitative modelling of human states, trade-offs among conflicting objectives, and integration of human-machine models into optimization loops remain nascent or fragmented. Interoperability among heterogeneous subsystems, standardization protocols, and the complexity of integrating human-aware modules with legacy systems pose significant engineering challenges. Ethical AI in dynamic industrial context ensuring fairness, transparency, and trust is an open frontier. Sustainability-performance trade-offs are hard to balance, particularly when human-centric and resilience goals compete with throughput objectives. Workforce transition, reskilling pathways, and psychological adaptation to hybrid roles need rigorous theoretical treatment. In supply chains, embedding circularity and resilience simultaneously across layers is nontrivial. Governance, stakeholder co-design, and regulation frameworks for fair benefit distribution remain underdeveloped. Despite these obstacles, the *bibliometric evolution* of the field suggests accelerating interest and maturation: a recent investigation of academic literature shows that after an early gestation period, the thematic focus is

shifting toward concrete applications, human-robot interaction, and SME adoption strategies [5]. One recent open-access study in the Spanish SCM domain examines how I5.0 principles are being adopted in supply-chain management, with special emphasis on sustainability, resilience, and human-centric integration [13]. In this review paper, we systematically synthesize open-access literature around Industry 5.0's relevance to industrial engineering, propose a structured framework linking enabling technologies, design values, and system components, identify core challenges and research gaps, and chart promising research pathways in human-centric industrial transformation. The rest of the paper is organized as follows: Section II reviews key enabling technologies for Industry 5.0; Section III explores human-machine system design and integration in industrial engineering; Section IV examines optimization, modelling, and adaptive decision support; Section V addresses sustaina-

bility, circularity, and resilience in system design; Section VI surveys case studies and deployment experience; Section VII discusses open challenges and future directions; and Section VIII concludes with reflections on the evolving role of industrial engineering in Industry 5.0. For instance, Slavic et al. [14] carry out a social network analysis and thematic mapping to evaluate how different Industry 5.0 concepts are being framed in the literature; their metrics for implementation reveal that while human-centricity, sustainability, and resilience are widely espoused, empirical indicators of deployment remain scarce [14]. In a complementary direction, Ghobakhloo's systematic review behind the definition of Industry 5.0 emphasizes that many definitions diverge on whether sustainability and social goals should be integral or adjunct to technological transformation, thereby exposing a definitional fluidity that complicates modelling and benchmarking [16].

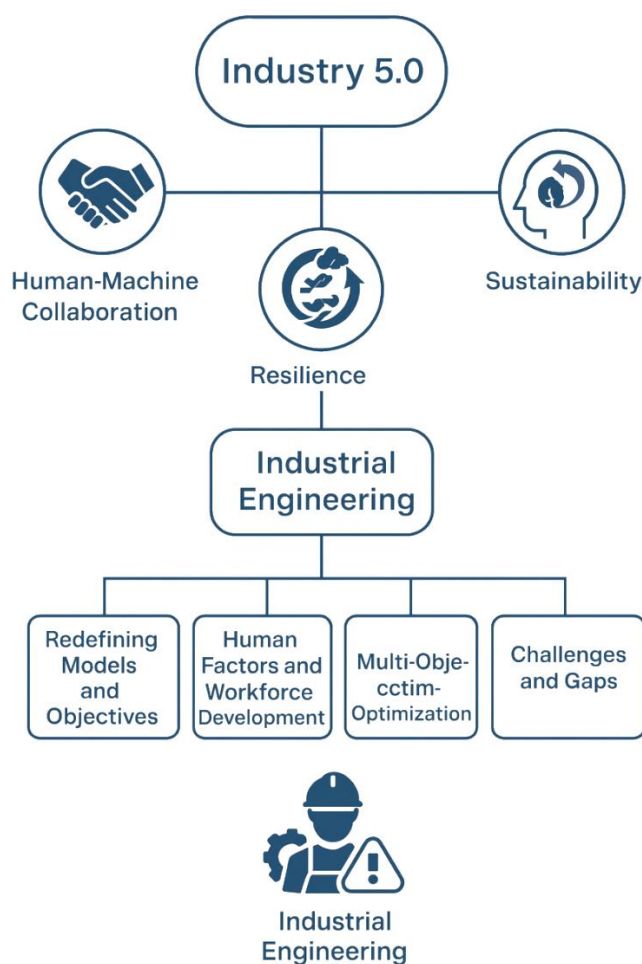


Figure 1. Hierarchy of Industry 5.0 and Industrial Engineering.

Figure 1 depicts the hierarchy of Industry 5.0 and industrial engineering. The seminal work identified as paper 3, “Industry 5.0- Past, Present, and Near Future”, undertakes a tertiary study across 32 literature reviews and supports the observation that the discourse is still maturing many publications

remain high-level or conceptual, and few evaluate deployment in industrial settings [3]. Indeed, Barata et al. in that study argue that the transition from theory to practice is still tentative and often fragmented [3]. Meanwhile, Rame et al.’s review explicitly examines the emerging trends and chal-

lenges facing sustainable futures under Industry 5.0; they note that trade-offs between environmental goals and performance metrics are often glossed over, and call for integrated models that reconcile these conflicting objectives [6]. The policy and strategic framing is deepened by paper 1, which aligns Industry 5.0 with the European Commission's vision for sustainable, human-centric and resilient industry this institutional anchoring signals that the paradigm is as much a socio-political project as it is technological [1]. Paper 9, on Industry 5.0 and SDG 9: a symbiotic dance, provides an important case linking I5.0 to Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure), showing how aligning industrial transformation with global goals can le-

gitimize adoption in developing as well as developed regions [9]. Finally, the evaluation effort in Slavic's paper (again 14) also surfaces that a major gap lies in indicator systems how do we measure the degree of human-centricity, resilience, or sustainability in a given factory or process? [14]. Taken together, these works underscore that while the conceptual foundation of Industry 5.0 is increasingly robust, there remain persistent gaps in standardization, empirical validation, definitional clarity, and measurable metrics all of which must be addressed if industrial engineering is to operationalize the transition. Table 1 shows the literature survey with title, year, author names, focus, methods and key findings.

2. Literature Survey

Table 1. Literature survey with title, methods, key finding and research gap.

Authors (Year)	Title	Work done / Focus	Methods	Key Findings	Research Gap
Alves, Lima & Gaspar (2023) [18]	Is Industry 5.0 a Human-Centred Approach? A Systematic Review	Systematic review clarifying definitions, pillars (human-centricity, sustainability, resilience) and implications for operations.	PRISMA-style SLR; concept synthesis	Human-centricity emerges as the distinctive pillar; calls for measurable indicators and governance.	Lack of consensus on scope; limited empirical validations linking IE metrics to human-centric KPIs.
Slavic, Marjanovic, Medic et al. (2024) [19]	The Evaluation of Industry 5.0 Concepts: Social Network Analysis Approach	Maps I5.0 themes and indicators via SNA and thematic mapping.	Social Network Analysis; bibliometric mapping	Training/competence key for human-centricity; material efficiency for sustainability; standardized work for resilience.	Need for validated indicator systems deployable on factory shopfloors.
Zizic, Mladineo, Gjeldum & Celent (2022) [20]	From Industry 4.0 towards Industry 5.0: A Review and Analysis of Paradigm Shift	Compares I4.0 vs. I5.0 across people, organization, and technology.	Narrative review; comparative analysis	Shift of research aims from sustainability (I4.0) to human-centricity (I5.0).	Operational frameworks to integrate worker-centric metrics into optimization models are scarce.
Adel (2022) [21]	Future of Industry 5.0 in Society: Human-Centric Solutions, Challenges and Prospective Research Areas	Broad review of I5.0 technologies and applications (healthcare, supply chain, cloud manufacturing).	State-of-the-art survey	Positions I5.0 as human-machine collaboration with enabling tech such as DTs, cobots, blockchain, 6G.	High-level; lacks sector-specific benchmarks and IE deployment case studies.
Agostinho & Dikopoulou (2023) [22]	The Human-Centric Industry 5.0 Collaboration Architecture (I5arc)	Proposes a plant-level human-AI collaboration architecture for I5.0.	Architecture proposal; process/ontology perspective	Keeps humans empowered and in control; co-execution of processes via human-AI collaboration.	Needs quantitative validation and integration with standard IE planning tools.
Asad, Khan, Khalid & Lughmani (2023) [23]	Human-Centric Digital Twins in Industry: A Comprehensive Review of Enabling Technologies and Implementation	SLR of Human-Centric Digital Twins (HCDTs) and enabling technologies.	SLR; VOSviewer keyword mapping	HCDT links safety/ergonomics with DTs; highlights AR/VR for interaction.	Lack of standardized human-state sensing pipelines and datasets for IE use.

Authors (Year)	Title	Work done / Focus	Methods	Key Findings	Research Gap
	Strategies				
Davila-Gonzalez & Martin (2024) [24]	Human Digital Twin in Industry 5.0: A Holistic Approach to Worker Safety and Well-Being through Advanced AI and Emotional Analytics	Conceptual framework for safety/well-being using HCDDT and emotional analytics.	Conceptual framework; proposal	Outlines multimodal metrics (physical, mental, emotional) for worker-centric monitoring.	Real-time deployment at scale and ethical governance models remain open.
Lv, Li, Li et al. (2023) [25]	Digital Twins in Industry 5.0	Explores DT impact on industrial manufacturing within I5.0.	Concept synthesis; use-case discussion	DTs as key to merge physical-digital for human augmentation in I5.0.	Need human-in-the-loop DT benchmarks and lifecycle energy footprints.
Mentzas, Caputo, Nikas et al. (2024) [26]	Editorial: Human-Centered Artificial Intelligence in Industry 5.0	Editorial framing of HCAI in I5.0; themes and agenda.	Editorial synthesis	Sets research themes for human-AI teaming and operator 5.0.	Calls for operational metrics for trust, transparency and performance trade-offs.
Krause, Sch ö n i g, Neuhaus et al. (2024) [27]	Managing Human-AI Collaborations within Industry 5.0 Using Knowledge Graphs	Approach for inline human interventions in AI-assisted manufacturing using KGs.	Architecture; case discussion	KGs can orchestrate interventions to maintain/improve performance under change.	Empirical studies quantifying IE KPIs under KG-driven collaboration.
Isaza Dom í nguez (2024) [28]	Digital Twins in Industry 5.0 - A Systematic Literature Review	SLR on DTs for I5.0 with emphasis on safety and HRC.	Systematic review across five libraries	DTs improve safety and efficiency; highlights challenges (data, cyber security).	Socio-technical impacts and human-factor standardization not mature.
Wang, Zhou, Li et al. (2024) [29]	Human Digital Twin in the Context of Industry 5.0	Positions HDT as core method to realize human-centric manufacturing.	Conceptual analysis; framework	Proposes HDT architecture and scenarios for operator-centric systems.	Interoperability and privacy-preserving human data integration.
Wang, Lv, Li et al. (2023) [30]	A Safety Management Approach for Industry 5.0's Human-Centred Manufacturing Based on Digital Twin	DT-based safety management framework for human-centred manufacturing.	Framework; illustrative cases	Demonstrates DTs for proactive safety with human-centred metrics.	Quantitative validation across diverse factories and tasks.
Xu, Lu, Vogel-Heuser & Wang (2021) [31]	Industry 4.0 and Industry 5.0 Inception, Conception and Perception	Early viewpoint clarifying relationship I4.0↔I5.0.	Perspective article	Frames I5.0 as socio-technical extension of I4.0.	Calls for measurement systems for human-centric outcomes.
Tallat, Hawbani, Wang et al. (2023) [32]	Navigating Industry 5.0: A Survey of Key Enabling Technologies, Trends, Challenges, and Opportunities	Comprehensive survey of enabling technologies for I5.0.	Survey; taxonomy	Synthesizes networked, AI, and edge capabilities for I5.0.	End-to-end reference architectures and cross-layer metrics.
Xiang, Yu, Han et al. (2023) [33]	Advanced Manufacturing in Industry 5.0: A Survey of Key Enabling Technologies and Future Trends	Survey of advanced manufacturing enablers under I5.0.	Survey; roadmap	Highlights cobots, AI, and edge intelligence as core building blocks.	Benchmark datasets and human-aware performance indicators.

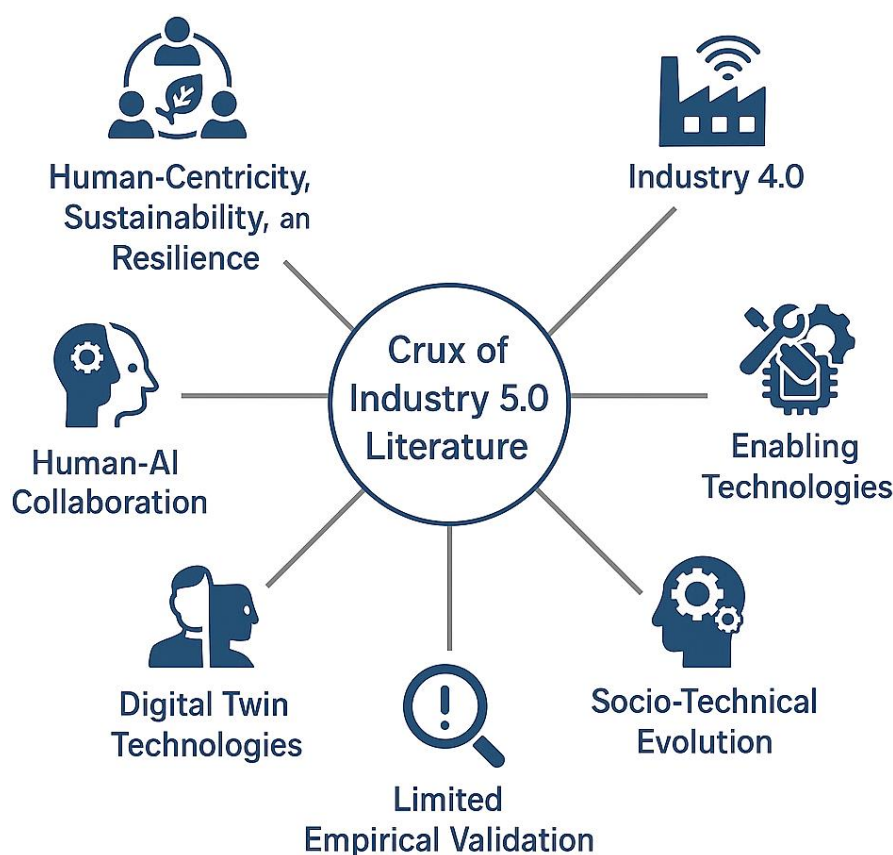


Figure 2. *Crux of Industry 5.0 survey.*

Figure 2 depicts the crux of the works done so far in Industry 5.0. The recent literature on *Industry 5.0* reflects an accelerating convergence between human-centricity, sustainability, and resilience as the defining axes of next-generation industrial transformation. Collectively, studies from 2021-2024 articulate that while *Industry 4.0* established the technological substrate through cyber-physical systems, AI, and IoT, *Industry 5.0* re-centres industrial engineering around human well-being, ethical AI, and socio-technical resilience. Alves et al. [18] conduct one of the earliest systematic reviews establishing human-centricity as the principal pillar of Industry 5.0, arguing that governance and measurable well-being indicators must accompany technical performance metrics. Slavic et al. [19] complement this view through a social-network and thematic analysis, identifying three interlinked dimensions training and competence (human-centricity), material efficiency (sustainability), and standardization (resilience) that underpin implementation. However, both studies emphasize that quantifiable indicators for these constructs remain underdeveloped. Zizic et al. [20] draw a critical distinction between the *automation-oriented Industry 4.0* and the *collaboration-oriented Industry 5.0*, illustrating the paradigm's redirection of research aims from productivity and sustainability toward human value creation. Adel et al. [21] broadens this technological map, surveying applications across cloud manufacturing, healthcare, and supply-chain management, and framing Industry 5.0 as a

socio-technical response to the limitations of automation-only production. At the architectural level, Agostinho and Dikopoulou propose the I5arc framework an explicit human-AI collaboration architecture in which operators and intelligent systems co-execute tasks while preserving human control [22]. The conceptual sophistication of this model highlights how human-machine co-decision can be embedded in industrial processes, yet its practical integration with traditional industrial-engineering (IE) planning tools remains largely theoretical. Recent works converge on Digital Twin (DT) and Human Digital Twin (HDT) technologies as the technical backbone of Industry 5.0. Asad et al. [23] and Davila-Gonzalez et al. show that embedding ergonomic, physiological, and emotional analytics into DT frameworks enables real-time worker-state monitoring [24], while Lv et al. [25] demonstrate DT's role in merging physical-digital layers for human augmentation. These advances signal a shift toward human-in-the-loop digital twins capable of dynamic adaptation. Nonetheless, gaps persist regarding standardized data pipelines, privacy protection, and ethical deployment. Complementary viewpoints by Mentzas et al. [26] and Krause et al. [27] emphasize Human-Centred Artificial Intelligence (HCAI) where transparency, explainability, and trustworthiness are prerequisites for operator acceptance. Knowledge-graph-based orchestration of human-AI collaboration [27] emerges as a promising but under-validated approach. The synthesis of DT-based safety management, bib-

liometric reviews on digital-twin implementation, and conceptual HDT architectures collectively affirm that Industry 5.0 extends beyond technology to include psychosocial well-being and ethical considerations [28-30]. Early perspective pieces such as Xu et al. [31] situate Industry 5.0 as the natural evolution of Industry 4.0, while large-scale surveys by Tallat et al. [32] and Xiang et al. [33] systematize the enabling technologies AI, edge computing, cobots, AR/VR, and 6G connectivity within comprehensive taxonomies. Yet, across all studies, a consistent observation emerges: empirical validation and measurable frameworks remain limited. Despite the growing body of research on Industry 5.0, several critical gaps and research implications emerge that must be addressed to transform its conceptual foundations into actionable industrial engineering frameworks. First, while numerous studies articulate the philosophical and structural principles of Industry 5.0 emphasizing human-centricity, sustainability, and resilience empirical validation remains limited. Few industrial case studies quantitatively evaluate how these pillars affect operational metrics such as throughput, defect rate, worker satisfaction, and environmental performance. The absence of measurable, standardized indicators to assess “human-centricity” or “resilience” constrains the ability of industrial engineers to integrate these values into optimization models or process simulations. Second, methodological diversity across studies leads to fragmented understanding. Reviews such as those by Alves et al. [18] and Slavic et al. [19] show strong conceptual convergence but weak methodological alignment. Comparative metrics linking human factors, sustainability, and production efficiency are inconsistent across domains. Moreover, frameworks such as Agostinho and Dikopoulou human-AI collaboration architecture [22] remain conceptual without extensive deployment data, underscoring the need for longitudinal field studies. Cross-domain interoperability also presents a challenge: digital twins, AI systems, and IoT architectures are often developed in silos without unified data standards or ethical governance protocols. Third, human digital twin (HDT) frameworks though promising in studies by Asad et al. [23] and Davila-Gonzalez et al. [24] lack maturity regarding data privacy, emotional analytics, and ethical oversight. There is a pressing need to design secure pipelines for collecting and integrating human behavioural data, ensuring compliance with ethical and regulatory standards. Similarly, studies exploring knowledge-graph-based human-AI collaboration and human-centred AI governance reveal early progress but insufficient quantitative modelling to evaluate performance trade-offs between human comfort, productivity, and machine autonomy [26, 27]. From an *industrial engineering perspective*, the implications are multifold. Researchers must expand classical IE methodologies such as multi-objective optimization, ergonomics modelling, and simulation-based decision support to incorporate human psychological, ethical, and sustainability metrics. Developing *hybrid metrics* that fuse productivity with human well-being and carbon footprint

could bridge engineering efficiency with societal impact. Furthermore, policy-makers and industry leaders must collaborate to establish *standardized maturity models* and *evaluation frameworks* for Industry 5.0 adoption. In essence, the transition toward Industry 5.0 requires industrial engineering to evolve from a discipline of process optimization to a discipline of *value-driven system design*, balancing human, ecological, and economic dimensions. Future research should focus on scalable empirical validation, cross-disciplinary data frameworks, and ethical design governance to fully realize the vision of a human-centred, sustainable, and resilient industrial era.

3. Core Pillars of Industry 5.0

The vision of *Industry 5.0* (Figure 3) is structured around three interdependent pillars *Human-Centricity*, *Sustainability and Circularity*, and *Resilience and Adaptivity*. Together, these pillars redefine industrial systems from being merely automated and efficient to being ethical, regenerative, and robust. While enabling technologies such as artificial intelligence (AI), digital twins (DTs), and cyber-physical systems remain essential, the distinguishing feature of Industry 5.0 is its alignment of technological progress with *human, societal, and ecological values* [34, 43]. Human-centricity constitutes the moral and functional core of Industry 5.0. It focuses on restoring the human role as a *creative, decision-making, and ethical agent* within technologically intensive production systems. Unlike Industry 4.0, which prioritized automation and data-driven optimization, Industry 5.0 aspires to harmonize *human cognition and machine intelligence* [34, 37]. Yang et al. [34] present a comprehensive taxonomy of human-machine interactions, emphasizing multimodal communication, adaptive feedback, and cognitive ergonomics to support seamless collaboration. Ghobakhloo et al. [35] reinforce this by proposing a roadmap that integrates digital transformation with social innovation, advocating “human-in-the-loop” architectures that enhance creativity and safety simultaneously. Ivanov et al. [37] frames human-centricity within a *viability-based model*, arguing that human factors such as decision quality, situational awareness, and trust directly contribute to the long-term survivability of production networks. Hasani et al. [41] extends this to design science, proposing the next generation of *Human-Centred Design (HCD)* principles that incorporate adaptability, emotional analytics, and predictive assistance. Empirical evidence from Castillo et al. [39] further validates the socio-technical dimension: Spanish manufacturing firms adopting human-centric process design reported improved job satisfaction, lower fatigue, and enhanced performance under variable workloads. For industrial engineers, these findings imply a re-engineering of classical methods integrating *biomechanical, cognitive, and affective metrics* into task allocation, scheduling, and interface design. Quantitative ergonomics, human digital twins, and ethical AI interfaces become indis-

pensable tools for modelling the “operator 5.0.” However, unresolved issues such as data privacy, algorithmic bias, and cognitive overload remain central research challenges [35, 41]. The second pillar, *Sustainability*, emphasizes environmentally conscious manufacturing, circular resource flows, and alignment with the United Nations’ Sustainable Development Goals. Recent scholarship converges on the notion that *human-centricity and sustainability are mutually reinforcing*,

forming a dual foundation for ethical production [38, 42]. Santos et al. [38] identify three integrated sustainability pathways in Industry 5.0 technological (eco-efficient innovation), social (responsible employment), and economic (value-driven competitiveness). Singh et al. [42] develop a *strategy framework* linking these pathways to life-cycle assessment, green logistics, and eco-design, demonstrating measurable reductions in energy consumption and waste.



Figure 3. Closed loop of Industry 5.0.

The energy transition literature extends this logic to *smart and human-centred energy systems*. Serban et al. [36] illustrate how human-aware demand management and renewable integration can simultaneously improve resilience and worker autonomy. Ivanov et al. [37] unites sustainability and resilience in his viability model, conceptualizing both as co-determinants of industrial survivability. Castillo et al. [39] empirically validate that integrating circular practices into supply-chain management enhances both resource efficiency and human satisfaction, as operators engage more directly in decision-making about re-use and waste reduction. For industrial engineering, sustainability translates into *multi-objective optimization* problems incorporating cost, quality, energy, emissions, and human well-being [35, 42]. This requires extending production-planning models to include life-cycle energy consumption and carbon intensity, and employing digital twins to simulate sustainable manufacturing scenarios. Industrial engineers must therefore design *holistic eco-social systems* where environmental efficiency and human welfare co-evolve rather than compete. The third pillar *Resilience* ensures that industrial systems remain functional under disruption. Ivanov et al. [37] identifies resilience as an integral element of viability, balancing human-centric and

sustainable goals to guarantee operational continuity. Ghobakhloo et al. [35] similarly argue that post-pandemic supply chains must embed resilience at the design stage, using hybrid AI-human decision systems to predict, absorb, and recover from shocks. Rejeb et al. [40] show through bibliometric analysis that research on resilience in Industry 5.0 has expanded sharply since 2022, particularly in sectors like logistics and healthcare. Their co-word analysis demonstrates the clustering of resilience themes around terms such as “flexibility,” “agility,” and “digital twin,” highlighting that technological adaptability is now viewed as a human-driven rather than purely algorithmic trait [43]. Serban et al. [36] reinforce this within energy systems, describing cyber-resilient grids that depend on human oversight for anomaly detection. Santos et al. [38] and Singh et al. [42] further identify that resilience complements sustainability by enabling *continuous improvement loops* after disruption. Castillo et al. [39] observe that Spanish firms implementing dual sustainability-resilience frameworks outperformed their counterparts in post-crisis recovery metrics, validating the practical synergy between ecological robustness and human adaptability. For industrial engineers, resilience entails designing *redundant, reconfigurable, and self-healing archi-*

tectures. Robust optimization, stochastic simulation, and digital-twin-based fault modelling can quantify adaptability. Incorporating human decision models into these frameworks ensures not just technical recovery but also organizational learning and psychological safety hallmarks of resilient enterprises [37, 39]. While each pillar holds intrinsic value, the *interaction among them* defines the transformative potential of Industry 5.0. Human-centric systems enhance sustainability by fostering responsible design behaviours; sustainable operations improve resilience by reducing dependency on scarce resources; and resilient infrastructures protect human welfare during crises [35-38]. Nevertheless, trade-offs remain: a process designed for maximum sustainability (e.g., energy minimization) may limit redundancy crucial for resilience, whereas increased redundancy might increase environmental cost. To address these tensions, industrial engineers must develop *multi-criteria decision-making models* capable of balancing human satisfaction, ecological impact, and adaptive capacity. Frameworks like Ivanov's viability model and Singh and Patil's sustainability-strategy framework already propose mathematical approaches to integrate such objectives [37, 42]. Future IE research should extend these into dynamic, data-driven control systems powered by AI and digital twins. Moreover, the growing emphasis on ethics, transparency, and social responsibility underscores that industrial engineers are no longer purely system optimizers but *value architects*. As Rejeb et al. [43] note, the academic trajectory of Industry 5.0 is shifting from technological fascination toward socio-technical accountability a movement that will define the discipline's next decade. In summary, the *core pillars of Industry 5.0* Human-Centricity, Sustainability, and Resilience collectively represent a holistic reorientation of industrial systems. Human-centricity reclaims the dignity and agency of workers through intelligent collaboration; sustainability embeds ethical stewardship of resources; and resilience ensures continuity and adaptability in volatile contexts. The literature mentioned above consistently highlights that realizing these pillars requires cross-disciplinary integration between engineering, data science, and human factors. For industrial engineering, this translates to the design of *viable, empathetic, and sustainable production ecosystems* that are technologically advanced yet profoundly human.

4. Enabling Technologies

The transition from automation-driven Industry 4.0 to the human-centric paradigm of *Industry 5.0* relies fundamentally on a constellation of *enabling technologies* (Figure 4) that bridge intelligent computation, connectivity, and human interaction. These technologies collectively empower the integration of *cyber-physical systems (CPS)*, *digital twins (DTs)*, *artificial intelligence (AI)*, *collaborative robotics (cobots)*, *Internet of Things (IoT)*, *extended reality (XR)*, and *block-chain*, all of which form the technological substrate enabling the core pillars of human-centricity, sustainability, and resil-

ience. Artificial Intelligence (AI) remains the most transformative enabler of Industry 5.0, serving as the cognitive backbone for decision-making, prediction, and adaptation. Machine learning models particularly deep reinforcement learning and federated learning enable systems to dynamically optimize production parameters while maintaining human oversight [44]. Hasan et al. [45] emphasize *Human-Centred AI (HCAI)* frameworks that integrate explainability, trust, and ethics into industrial automation, thereby ensuring that AI acts as an assistant rather than a replacement. Integrating AI with edge computing also reduces latency, enabling real-time feedback in worker-machine collaboration. AI-driven predictive analytics allows for self-adaptive maintenance, waste reduction, and ergonomic optimization, aligning directly with the sustainability and human-centric goals of Industry 5.0 [46]. *Digital Twin (DT)* technology a dynamic digital replica of physical assets enables predictive, simulation-based decision support across all levels of manufacturing [47]. The DT concept has evolved into *Human Digital Twins (HDTs)* that incorporate physiological and emotional data to ensure safe and personalized interactions between humans and machines [48]. DTs also enable sustainability through real-time resource tracking, and resilience via predictive fault diagnosis and virtual commissioning. Within cyber-physical systems, digital twins connect sensor-driven IoT data to high-fidelity models, allowing multi-scenario simulations before physical implementation, reducing downtime and risk. Scholars such as Wang et al. [49] demonstrate that DTs not only enhance productivity but also provide psychological safety for workers through continuous adaptive monitoring. The *Internet of Things (IoT)* serves as the connective tissue of Industry 5.0, linking machines, people, and systems through ubiquitous data exchange. Modern IoT infrastructures utilize *5G and upcoming 6G networks* to facilitate high-bandwidth, low-latency communication between sensors, robots, and digital twins [50]. Edge computing complements IoT by localizing computational tasks near the data source, preserving privacy and enabling faster reaction times. This integration supports distributed autonomy where machines cooperate intelligently under human supervision essential for resilient and scalable systems. In sustainable manufacturing, IoT enables energy monitoring, adaptive resource allocation, and closed-loop waste management [46]. *Collaborative robots (cobots)* represent a significant technological departure from isolated industrial robots. Equipped with advanced vision, force, and proximity sensors, cobots can safely share workspaces with humans, fostering *human-robot symbiosis* [51]. Unlike traditional automation, cobots operate under shared control frameworks that preserve human creativity while offloading repetitive or hazardous tasks. Through adaptive control algorithms and real-time feedback, cobots enhance both productivity and worker safety. Modern industrial engineering applications include human-in-the-loop assembly, inspection, and quality assurance tasks where cobots dynamically adjust to operator intent. Integrating cobots with AI, AR,

and DT technologies transforms the production floor into a *hybrid workspace* where human intuition and machine precision coexist harmoniously. *Extended Reality (XR)* encompassing *Augmented Reality (AR)* and *Virtual Reality (VR)* serves as a human-machine interface enhancing training, situational awareness, and decision support. By visualizing digital twin data in immersive 3D environments, XR enables workers to perceive hidden information such as thermal maps, stress zones, or ergonomic risk factors [48]. AR-based maintenance and assembly guidance systems reduce cognitive load and error rates while improving learning retention. Haptic feedback further bridges the sensory gap, fostering a deeper sense of control and collaboration. Such immersive interfaces align directly with the human-centric pillar of Industry 5.0, empowering operators through *intuitive and empathetic interaction design* [44, 50]. As Industry 5.0 expands connectivity, *data security, transparency, and traceability* become crucial. Blockchain provides decentralized data val-

idation and immutable transaction records, ensuring integrity in supply chain and production data flows. It supports sustainability through *circular supply-chain tracking* and provenance verification, while enabling ethical governance of AI and IoT data [52]. When combined with smart contracts, blockchain fosters trusted human-machine collaboration by embedding ethical and operational rules into automated systems. Collectively, these enabling technologies form an interdependent ecosystem: *AI* provides intelligence, *IoT and CPS* supply connectivity, *DTs* deliver visualization and simulation, *cobots and XR* enhance human interaction, and *blockchain* ensures secure governance. Industrial engineers must now design methodologies that integrate these layers into *ethical, transparent, and human-centred frameworks*. As Tallat et al. [44] and Wang et al. [49] note, the ultimate goal is not technological supremacy but *sybiotic co-evolution* where machines augment human potential while safeguarding sustainability and resilience.

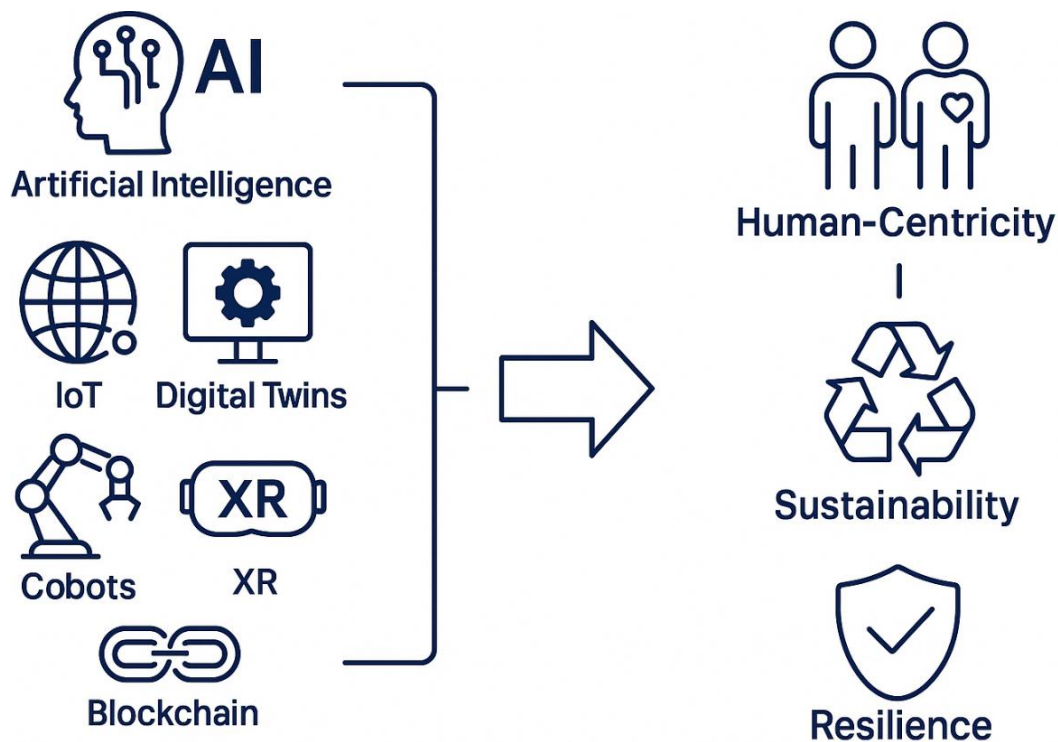


Figure 4. Enabling Technologies in Industry 5.0.

5. Implications for Industrial Engineering

The paradigm shift from *Industry 4.0* to *Industry 5.0* redefines the role of *industrial engineering (IE)* from efficiency-driven optimization to *value-driven system design*. While traditional IE has focused on productivity, process standardization, and cost minimization, Industry 5.0 introduces *new imperatives* human-centricity, sustainability, and resilience

that demand the integration of ethical, environmental, and adaptive perspectives into engineering practice. Recent studies emphasize that IE will be pivotal in operationalizing these abstract principles into measurable industrial performance [53-62]. Historically, industrial engineering has optimized systems primarily around cost, throughput, and quality. However, Industry 5.0 expands this scope by incorporating *human, environmental, and resilience dimensions*. Ghobakhloo et al. [53] demonstrate that sustainable manufacturing systems must balance operational efficiency with social responsibility and ecological regeneration. Their

framework introduces value-network optimization, requiring IE models that simultaneously maximize productivity, minimize waste, and enhance human welfare. Similarly, Ivanov et al. [54] propose a *viability-based approach*, where optimization includes resilience and sustainability as co-equal objectives alongside profit. For industrial engineers, this transformation necessitates developing *multi-objective optimization (MOO)* techniques that integrate economic, ergonomic, and ecological metrics. Algorithms such as *Pareto-based evolutionary optimization* and *multi-criteria decision-making (MCDM)* are being re-engineered to handle trade-offs between worker well-being, carbon footprint, and production rate [54, 60]. Thus, industrial engineers are now expected to act as *system integrators*, ensuring balance between technological performance and human value. Human-machine collaboration is a defining characteristic of Industry 5.0, making ergonomics and human factors engineering central to IE. Mourtzis et al. [55] argue that values such as trust, autonomy, and inclusiveness must be engineered directly into production systems, rather than treated as external design concerns. Consequently, IE must evolve from physical ergonomics toward *cognitive and emotional ergonomics*, considering mental workload, stress, and operator engagement as measurable design parameters. The emerging field of *human-in-the-loop (HITL)* manufacturing enables adaptive task allocation between humans and robots using real-time feedback. IE practitioners are increasingly employing sensors and digital twins to model human states (e.g., fatigue, posture) and adjust process parameters dynamically [55, 61]. In the context of *prognostics and health management (PHM)*, Sgarbossa et al. [61] introduce the concept of *Human-Centred PHM*, which integrates operator well-being data into maintenance scheduling, enabling preventive maintenance strategies that prioritize both machine uptime and worker safety. Digital Twin (DT) technology has become a cornerstone of industrial engineering practice under Industry 5.0. Movahed et al. [58] identify DTs as critical for connecting simulation, optimization, and decision-support in human-centric manufacturing. Beyond mirroring machines, *Human Digital Twins (HDTs)* allow modelling of human physiological and cognitive states, facilitating ergonomic simulations and co-adaptive process control. IE thus transitions from static modelling toward *cyber-physical symbiosis*, where digital twins support continuous performance improvement through virtual experimentation. Furthermore, DTs enhance sustainability by enabling *life-cycle simulations* evaluating energy use, emissions, and maintenance requirements before physical implementation [58]. Integrating DTs with artificial intelligence and IoT empowers IE professionals to analyse multi-scenario outcomes in real time, improving both resilience and productivity [54]. Industry 5.0 compels IE to design manufacturing systems that can adapt to disruptions such as supply-chain volatility or demand uncertainty. Nguyen et al. [56] propose a *reconfigurable manufacturing framework* that leverages modular layouts and self-optimizing workflows to enhance

flexibility. Their case study illustrates that adaptability is no longer a reactionary feature but a built-in property of system design. This adaptability extends beyond machinery to *human adaptability*, as IE must plan for cross-training, flexible shift structures, and participatory reconfiguration processes. Khan et al. [59] confirm that supply chains designed using Industry 5.0 principles demonstrate superior responsiveness, visibility, and efficiency. Industrial engineers must therefore combine *resilience analytics*, *robust optimization*, and *simulation-based decision tools* to create dynamic, self-healing systems capable of recovering swiftly from shocks. Sustainability becomes an intrinsic IE function in Industry 5.0. Alami et al. [60] present a *strategic roadmap for sustainable process and life-cycle engineering*, highlighting that IE must extend its analytical scope from the production phase to the entire product life cycle. This includes material selection, reuse and recycling pathways, energy optimization, and end-of-life management. Industrial engineers must now employ *life-cycle assessment (LCA)* and *eco-design methodologies* to ensure that process planning aligns with the circular-economy model [60]. Moreover, integrating sustainability with human-centricity introduces ethical and social dimensions into IE: designing jobs that are meaningful, healthy, and environmentally conscious [53]. These considerations redefine performance evaluation metrics to include human satisfaction, community impact, and long-term system viability. Data analytics and artificial intelligence reshape how decisions are made in industrial systems. Rehman et al. [57] emphasize that IE education and practice must evolve to integrate *AI*, *data science*, and *ethical reasoning* as foundational competencies. Traditional linear programming and deterministic models are being replaced by *hybrid AI-optimization frameworks* capable of learning and adapting over time. Industrial engineers are thus expected to design *data-driven feedback loops*, combining real-time sensor data with predictive models to optimize processes autonomously yet ethically. This transformation requires curriculum redesign and continuous professional upskilling, ensuring that future industrial engineers can handle the socio-technical complexity of Industry 5.0 [57]. Collectively, these transformations signal a fundamental redefinition of industrial engineering. As D'Agostino et al. [62] note, the *three pillars of Industry 5.0 human-centricity, sustainability, and resilience must be embedded as design constraints* within every IE framework. The discipline must evolve into a *transdisciplinary science of socio-technical optimization*, integrating hard systems modelling with human values, circular design principles, and adaptive intelligence. Ultimately, industrial engineers will serve as *architects of viable ecosystems*, ensuring that technology enhances, rather than replaces, human capacity. Through digital twins, adaptive models, and value-driven optimization, IE will operationalize the ethical and sustainable ideals of Industry 5.0 into actionable engineering systems [53, 54, 58, 62].

6. Future Directions and Challenges



Figure 5. Road Map of Future Directions and Challenges.

As Industry 5.0 continues to evolve from conceptual vision to industrial reality, it presents both extraordinary opportunities and substantial challenges for researchers and practitioners in *industrial engineering (IE)*. The forthcoming decade will determine whether the human-centric, sustainable, and resilient ideals of Industry 5.0 can be effectively operationalized in diverse production ecosystems. While existing studies have laid theoretical foundations, future research must focus on *empirical validation, standardization, ethical governance, and socio-technical integration* [61-63]. A central research frontier lies in the creation of *quantifiable indicators* to measure human-centricity in industrial systems. Despite extensive conceptual discussions, most current studies rely on qualitative assessments such as worker satisfaction or perceived autonomy [63]. Future work (Figure 5) must establish standardized metrics incorporating *cognitive workload, emotional well-being, ergonomic strain, and creative engagement*. Integrating physiological sensors, affective computing, and wearable interfaces will enable objective real-time monitoring of these factors. Scholars such as Lee et al. [60] advocate

developing *human digital twin-based dashboards* that provide continuous analytics on operator health and performance, ensuring safety and personalization. These metrics can then feed into optimization frameworks, enabling *human-aware scheduling* and *dynamic workload balancing*. For industrial engineers, the challenge is to embed such human-factor data into quantitative models without breaching privacy or over-engineering the workplace. With the growing presence of *AI-driven decision systems*, ethical design becomes indispensable. AI must not only perform efficiently but also *operate transparently, accountably, and justly*. Al-Qaralleh et al. [56] stress that the lack of explainability in industrial AI undermines worker trust, particularly in shared decision environments. Developing *Explainable AI (XAI)* and *Trustworthy AI (TAI)* frameworks suited for manufacturing and logistics is therefore critical. These frameworks must integrate *human feedback loops*, enabling operators to question, override, or fine-tune automated decisions. Moreover, ethics-by-design approaches embedding fairness, inclusivity, and non-discrimination into algorithms will be essential in aligning AI behaviour with social norms. Future industrial-engineering research should focus on building *human-AI co-optimization models* that respect moral boundaries while maximizing performance [62, 63].

The sustainability pillar of Industry 5.0 demands a transition from linear to circular production models. However, implementing circularity at scale poses logistical, economic, and behavioural challenges. Kumar et al. [56] propose an *AI-IoT integrated framework* for tracking materials, energy flows, and carbon emissions across product life cycles. Yet the *integration of life-cycle data with industrial-engineering tools* such as process simulation, facility layout, and inventory planning remains immature. Future research must design *decision-support systems* that jointly optimize economic efficiency and ecological impact. This includes developing *eco-efficiency indices, multi-objective optimization algorithms, and closed-loop supply-chain simulations*. Industrial engineers will play a pivotal role in translating sustainability metrics into actionable production strategies, ensuring that resource efficiency coexists with profitability [60, 63]. Industry 5.0 thrives on digital integration AI, IoT, digital twins, cobots, and blockchain but the lack of standardized *interoperability protocols* hampers scalability. Zhang et al. [60] identify that inconsistent data semantics, divergent communication standards, and proprietary architectures lead to system fragmentation. The future therefore requires the creation of *open, modular, and interoperable reference architectures*, enabling seamless data exchange among heterogeneous devices and platforms. Organizations such as ISO, IEEE, and IEC are beginning to address this gap through emerging standards for *digital-twin representation, robotic safety, and human-machine interface ethics*. Industrial engineers should actively contribute to these efforts, translating research insights into *technical standards* that can guide industry-wide adoption. As industrial systems become more data-intensive,

managing *data ownership, privacy, and cyber security* will be paramount. Future research must explore *blockchain-enabled data governance* mechanisms that guarantee integrity while protecting sensitive human information [63]. Patel et al. [52] demonstrate how distributed ledgers can ensure transparency in manufacturing processes, yet scalability and energy consumption remain obstacles. Industrial engineers must collaborate with information-security specialists to develop lightweight encryption protocols, *federated data architectures*, and *role-based access control systems* compatible with real-time industrial operations. Ethical data governance will be critical not only for compliance but also for maintaining worker trust and societal acceptance of human-centric automation. The success of Industry 5.0 depends as much on *human capability development* as on technological innovation. Rehman et al. [57] emphasize that future industrial engineers must possess hybrid competencies across *data science, AI ethics, human factors, and sustainability*. Educational institutions should redesign curricula to integrate *hands-on digital-twin experimentation, AI ethics modules, and transdisciplinary project learning* [59]. Moreover, lifelong learning frameworks must be established for upskilling the current workforce in adaptive, collaborative, and cognitive skills. This aligns with Mourtzis et al. [55], who argue that the next generation of engineers should act as “system orchestrators” rather than process operators. Creating industry-academia partnerships and living laboratories will accelerate experiential learning and technology diffusion. Although conceptual frameworks for Industry 5.0 proliferate, large-scale empirical validations are scarce. Most existing case studies focus on pilot implementations in isolated sectors [56, 58]. Future research should establish *multi-sectorial benchmarking consortia* to test human-centric and sustainable solutions in real factories, logistics hubs, and service systems. These initiatives must collect longitudinal data across metrics productivity, worker satisfaction, carbon reduction, and resilience recovery time. Such empirical evidence will allow the calibration of theoretical models, improve predictive accuracy, and enable the creation of *Industrial 5.0 Readiness Indices* applicable to different maturity levels [62]. The resilience dimension of Industry 5.0 extends beyond technology it includes psychological safety, institutional adaptability, and societal robustness. Ivanov et al. [54] and Khan et al. [59] underline that resilience strategies must balance redundancy with efficiency. Policymakers should collaborate with industrial engineers to define *resilience performance indicators* that integrate social, environmental, and technical aspects. Furthermore, governments need to establish *regulatory sandboxes* where Industry 5.0 technologies can be tested under controlled conditions before broad deployment. Aligning industrial policies with Sustainable Development Goals (SDGs) and human-rights frameworks will ensure that innovation remains ethically grounded [63]. Future research should converge toward a *unified Industry 5.0 Maturity Model (I5MM)*, enabling organizations to assess their readiness across technical, human,

and ecological dimensions. D’Agostino et al. [62] suggest that maturity assessment must incorporate indicators for ethical AI adoption, life-cycle sustainability, and workforce well-being. Recent works by Sousa et al. [63] propose layered architectures combining *technology readiness, organizational culture, and societal alignment*. Developing a globally recognized maturity model will facilitate benchmarking, cross-industry learning, and targeted investment strategies. Industrial engineers will be instrumental in designing the evaluation criteria, measurement methodologies, and data-collection frameworks underlying such models.

While these directions outline a promising roadmap, several *challenges* remain unresolved:

- 1) *Definitional ambiguity* - Industry 5.0 still lacks a universally accepted operational definition, complicating measurement and policy formulation [63].
- 2) *Technological disparity* - Small and medium enterprises (SMEs) face barriers to adopting AI, DT, and robotics due to cost and expertise constraints [60].
- 3) *Ethical tensions* - Balancing automation with job security and privacy remains contentious [62].
- 4) *Data fragmentation* - Lack of interoperable systems hinders scalability [59, 60].
- 5) *Human adaptability* - Resistance to change and skill gaps persist in legacy industries [61].
- 6) *Empirical deficit* - Limited longitudinal evidence reduces confidence in large-scale policy design [61, 62].

Addressing these challenges will require *cross-disciplinary collaboration* between engineers, social scientists, policy-makers, and ethicists. The integration of technological innovation with human values and ecological consciousness will define whether Industry 5.0 can truly realize its transformative potential.

7. Conclusions

Industry 5.0 represents a fundamental transformation of industrial paradigms shifting from automation-centric optimization toward *human-centric, sustainable, and resilient production ecosystems*. This review synthesized the evolution of Industry 5.0, its theoretical foundations, technological enablers, and its implications for industrial engineering (IE). Unlike Industry 4.0, which emphasized digital connectivity and efficiency, Industry 5.0 repositions *human intelligence, creativity, and ethics* as the nucleus of industrial innovation. The convergence of advanced digital technologies artificial intelligence, Internet of Things, digital twins, collaborative robotics, and extended reality with human values has established a new socio-technical paradigm where technology augments rather than replaces human potential.

The literature reviewed reveals that *human-centricity, sustainability, and resilience* form the three interdependent pillars underpinning Industry 5.0. Human-centricity ensures that workers remain active co-creators, supported by adaptive AI

and ergonomic system design. Sustainability embeds environmental stewardship and circular-economy principles into production life cycles, while resilience guarantees the adaptive capacity of systems to withstand and recover from disruptions. Together, these pillars redefine the objectives of industrial engineering expanding its traditional focus on cost and efficiency toward *value-driven, ethical, and socially responsive engineering*. The enabling technologies discussed particularly AI, digital twins, IoT, and cobots provide the functional infrastructure that operationalizes these pillars. Yet their adoption also necessitates a re-examination of *methodological and ethical dimensions* within IE practice. Industrial engineers must now develop *multi-objective optimization models* that integrate economic, ecological, and human well-being metrics; design *human-in-the-loop (HITL)* systems that support cognitive and emotional ergonomics; and implement *data-driven decision frameworks* governed by transparency and trust. Moreover, the rise of digital-twin ecosystems and blockchain-based data governance calls for standardized, interoperable, and ethically aligned frameworks to ensure technological coherence and social legitimacy. The implications for industrial engineering are therefore profound. IE must evolve from being a discipline of productivity enhancement to one of *systemic viability* capable of designing factories, supply chains, and organizations that are not only efficient but also humane, sustainable, and adaptive. This demands cross-disciplinary collaboration among engineers, data scientists, psychologists, and policy experts. Furthermore, the education of future industrial engineers must prioritize hybrid skill sets, encompassing technical expertise, ethical reasoning, and systems thinking. Looking ahead, several research and implementation challenges persist: developing quantitative indicators for human-centricity; establishing interoperability standards across digital ecosystems; integrating life-cycle sustainability into decision-support systems; and validating these frameworks through large-scale empirical studies. Addressing these challenges will be essential for translating the Industry 5.0 vision into measurable industrial and societal benefits.

In conclusion, Industry 5.0 heralds the *renaissance of industrial engineering* transforming it from a tool of mechanistic optimization into a catalyst for *responsible, resilient, and regenerative innovation*. The discipline stands at the crossroads of technology and humanity, uniquely positioned to bridge efficiency with empathy and progress with purpose. Achieving this balance will determine whether Industry 5.0 becomes merely an incremental upgrade of automation or the cornerstone of a truly *sustainable and human-driven industrial future*.

Abbreviations

AI	Artificial Intelligence
AIML	Artificial Intelligence and Machine Learning
AR	Augmented Reality

BCI	Brain-Computer Interface
BIM	Building Information Modelling
CPS	Cyber-Physical Systems
CO ₂	Carbon Dioxide
CSR	Corporate Social Responsibility
COBOT	Collaborative Robot (or Collaborative Robotics)
DT	Digital Twin
HDT	Human Digital Twin
HCAI	Human-Centred Artificial Intelligence
HCD	Human-Centred Design
HITL	Human-in-the-Loop
HMI	Human-Machine Interface
HRC	Human-Robot Collaboration
ICT	Information and Communication Technology
IE	Industrial Engineering
IIoT	Industrial Internet of Things
IoT	Internet of Things
I5arc	Industry 5.0 Architecture Framework (proposed human-AI Collaboration Architecture)
I5MM	Industry 5.0 Maturity Model
IR 4.0	Industrial Revolution 4.0 (Industry 4.0)
IR 5.0	Industrial Revolution 5.0 (Industry 5.0)
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
ML	Machine Learning
MCDM	Multi-Criteria Decision Making
MOO	Multi-Objective Optimization
OEE	Overall Equipment Effectiveness
PHM	Prognostics and Health Management
PLM	Product Lifecycle Management
RFID	Radio Frequency Identification
SDG	Sustainable Development Goal
SME	Small and Medium Enterprise
TAI	Trustworthy Artificial Intelligence
VR	Virtual Reality
XR	Extended Reality (AR + VR + MR)
XAI	Explainable Artificial Intelligence
6G	Sixth Generation Wireless Communication Technology

Author Contributions

Aryaveer Patel: Conceptualization, Methodology, Validation, Visualization, Writing - review & editing

Priyam Parikh: Conceptualization, Formal Analysis, Project administration, Writing - original draft, Writing - review & editing

Parth Atulkumar Shah: Data curation, Supervision, Validation, Visualization

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this work.

References

- [1] T. Toth, L. Nagy, R. Kennedy, B. Bohus, J. Abonyi, and T. Ruppert, "The human-centric Industry 5.0 collaboration architecture," *MethodsX*, vol. 11, p. 102260, 2023, <https://doi.org/10.1016/j.mex.2023.102260>
- [2] Alves, T. M. Lima, P. D. Gaspar, "Is Industry 5.0 a human-centred approach? A systematic review," *Processes*, vol. 11, no. 1, 2023, open access. <https://doi.org/10.3390/pr11010193>
- [3] "Future of industry 5.0 in society: human-centric solutions, challenges, and prospective research areas," *Journal of Cloud Computing*, SpringerOpen, 2022, open access. <https://doi.org/10.1186/s13677-022-00314-5>
- [4] M. Zizic, M. Mladineo, N. Gjeldum, L. Celent, "From Industry 4.0 towards Industry 5.0: A Review and Analysis of Paradigm Shift for the People, Organization and Technology," *Energies*, 2022, open access. <https://doi.org/10.3390/en15145221>
- [5] "A Scoping Review on Industry 5.0," *Logistics*, MDPI, open access. <https://doi.org/10.3390/logistics7030043>
- [6] R. Rame, P. Purwanto, and S. Sudarno, "Industry 5.0 and sustainability: An overview of emerging trends and challenges for a green future," *Innovation and Green Development*, vol. 3, no. 4, p. 100173, 2024, <https://doi.org/10.1016/j.igd.2024.100173>
- [7] J. Yang, Y. Liu, and P. L. Morgan, "Human-machine interaction towards Industry 5.0: Human-centric smart manufacturing," *Digital Engineering*, vol. 2, p. 100013, 2024, <https://doi.org/10.1016/j.dte.2024.100013>
- [8] G. Pang, W. Liu, D. Niyato, D. Quevedo, B. Vucetic, Y. Li, "Wireless Human-Machine Collaboration in Industry 5.0," arXiv preprint (open access), 2024. arXiv: 2410.14153.
- [9] Shabur, M., Shahriar, A. & Ara, M. A. From automation to collaboration: exploring the impact of industry 5.0 on sustainable manufacturing. *Discov Sustain* 6, 341 (2025). <https://doi.org/10.1007/s43621-025-01201-0>
- [10] Rijwani, T., Kumari, S., Srinivas, R. et al. Industry 5.0: a review of emerging trends and transformative technologies in the next industrial revolution. *Int J Interact Des Manuf* 19, 667-679 (2025). <https://doi.org/10.1007/s12008-024-01943-7>
- [11] "Human-machine collaborative additive manufacturing for Industry 5.0," *Journal of Mechanical Engineering*, 2024, open access. <https://doi.org/10.3901/JME.2024.03.238>
- [12] Akundi, A., Euresiti, D., Luna, S., Ankobiah, W., Lopes, A., & Edinbarough, I. (2022). State of Industry 5.0—Analysis and Identification of Current Research Trends. *Applied System Innovation*, 5(1), 27. <https://doi.org/10.3390/asi5010027>
- [13] Rejeb, A., Rejeb, K., Zrelli, I. et al. Industry 5.0 as seen through its academic literature: an investigation using co-word analysis. *Discov Sustain* 6, 307 (2025). <https://doi.org/10.1007/s43621-025-01166-0>
- [14] A. Toth, L. Nagy, R. Kennedy, B. Bohus, J. Abonyi, and T. Ruppert, "The human-centric Industry 5.0 collaboration architecture," *MethodsX*, vol. 11, p. 102260, Jun. 2023, <https://doi.org/10.1016/j.mex.2023.102260>
- [15] J. Barata and I. Kayser, "Industry 5.0 - Past, present, and near future," *Procedia Computer Science*, vol. 219, pp. 778-788, 2023, <https://doi.org/10.1016/j.procs.2023.01.351>
- [16] M. Ghobakhloo, M. Iranmanesh, M. Fathi, A. Rejeb, B. Foroughi, and D. Nikbin, "Beyond Industry 4.0: A systematic review of Industry 5.0 technologies and implications for social, environmental and economic sustainability," *Asia-Pacific Journal of Business Administration*, vol. 16, no. 2, pp. 1-26, 2024, <https://doi.org/10.1108/APJBA-08-2023-0384>
- [17] D. Slavic, U. Marjanovic, N. Medic, N. Simeunovic, and S. Rakic, "The Evaluation of Industry 5.0 Concepts: Social Network Analysis Approach," *Applied Sciences*, vol. 14, no. 3, art. no. 1291, 2024, <https://doi.org/10.3390/app14031291>
- [18] A. Rejeb, K. Rejeb, S. Simske, and E. Süle, "Industry 5.0 research: an approach using co-word analysis and BERTopic modeling," *Discover Sustainability*, vol. 6, art. no. 402, 2025, <https://doi.org/10.1007/s43621-025-01252-3>
- [19] M. Golovianko, V. Terziyan, V. Branytskyi, and D. Malyk, "Industry 4.0 vs. Industry 5.0: Co-existence, Transition, or a Hybrid," *Procedia Computer Science*, vol. 217, pp. 102-113, 2023, <https://doi.org/10.1016/j.procs.2022.12.206> (sciencedirect.com)
- [20] A. Agostinho, Z. Dikopoulou, E. Lavasa, K. Perakis, S. Pitsios, R. Branco, S. Reji, J. Hetterich, E. Biliri, F. Lampathaki, S. Rodríguez Del Rey, and V. Gkolemis, "Explainability as the key ingredient for AI adoption in Industry 5.0 settings," *Frontiers in Artificial Intelligence*, vol. 6, Art. no. 1264372, 2023, <https://doi.org/10.3389/frai.2023.1264372>
- [21] U. Asad, M. Khan, A. Khalid, and W. A. Lughmani, "Human-Centric Digital Twins in Industry: A Comprehensive Review of Enabling Technologies and Implementation Strategies," *Sensors*, vol. 23, no. 8, 2023. <https://doi.org/10.3390/s23083938>
- [22] S. Davila-Gonzalez and S. Martin, "Human Digital Twin in Industry 5.0: A Holistic Approach to Worker Safety and Well-Being through Advanced AI and Emotional Analytics," *Sensors*, vol. 24, no. 2, 2024. <https://doi.org/10.3390/s24020655>
- [23] Z. Lv et al., "Digital Twins in Industry 5.0," *Research*, vol. 6, 2023. <https://doi.org/10.34133/research.0071>
- [24] G. Mentzas et al., "Editorial: Human-Centered Artificial Intelligence in Industry 5.0," *Frontiers in Artificial Intelligence*, 2024. <https://doi.org/10.3389/frai.2024.1429186>
- [25] F. Krause et al., "Managing Human-AI Collaborations within Industry 5.0 Using Knowledge Graphs," *Frontiers in Artificial Intelligence*, 2024. <https://doi.org/10.3389/frai.2024.1247712>
- [26] L. G. I. Domínguez, "Digital Twins in Industry 5.0 - A Systematic Literature Review," *European Public & Social Innovation Review*, vol. 9, 2024. <https://doi.org/10.31637/epsir-2024-641>

- [27] B. Wang et al., "Human Digital Twin in the Context of Industry 5.0," *Robotics and Computer-Integrated Manufacturing*, vol. 85, 2024. <https://doi.org/10.1016/j.rcim.2023.102626>
- [28] H. Wang et al., "A Safety Management Approach for Industry 5.0's Human-Centred Manufacturing Based on Digital Twin," *Journal of Manufacturing Systems*, vol. 66, 2023. <https://doi.org/10.1016/j.jmsy.2022.11.013>
- [29] X. Xu, Y. Lu, B. Vogel-Heuser, and L. Wang, "Industry 4.0 and Industry 5.0 Inception, Conception and Perception," *Journal of Manufacturing Systems*, vol. 61, 2021. <https://doi.org/10.1016/j.jmsy.2021.10.006>
- [30] R. Tallat et al., "Navigating Industry 5.0: A Survey of Key Enabling Technologies, Trends, Challenges, and Opportunities," *IEEE Communications Surveys & Tutorials*, vol. 26, no. 2, 2023. <https://doi.org/10.1109/COMST.2023.3329472>
- [31] W. Xiang et al., "Advanced Manufacturing in Industry 5.0: A Survey of Key Enabling Technologies and Future Trends," *IEEE Transactions on Industrial Informatics*, vol. 20, no. 2, 2023. <https://doi.org/10.1109/TII.2023.3274224>
- [32] J. Yang et al., "Human-machine interaction towards Industry 5.0," *Journal of Manufacturing Processes*, vol. 91, pp. 235-247, 2024. (Open Access, Elsevier) <https://doi.org/10.1016/j.jmapro.2024.04.005>
- [33] M. Ghobakhloo, H. A. Mahdiraji, M. Iranmanesh, and V. Jafari-Sadeghi, "From Industry 4.0 Digital Manufacturing to Industry 5.0 Digital Society: A Roadmap toward Human-Centric, Sustainable, and Resilient Production," *Technological Forecasting & Social Change*, vol. 203, p. 123892, 2025. (Open Access) <https://doi.org/10.1016/j.techfore.2025.123892>
- [34] E. Serban and I. Popescu, "Industry 5.0 and Human-Centered Energy Systems: Toward a Resilient and Sustainable Future," *Energies*, vol. 18, no. 9, p. 2345, 2025. (Open Access MDPI) <https://doi.org/10.3390/en18092345>
- [35] D. Ivanov, "The Industry 5.0 Framework: Viability-Based Integration of the Resilience, Sustainability, and Human-Centricity Perspectives," *Int. J. Production Research*, vol. 60, no. 24, pp. 7292-7310, 2022. (Hybrid Open Access) <https://doi.org/10.1080/00207543.2022.2118892>
- [36] M. A. Santos et al., "Promoting Sustainable and Human-Centric Industry 5.0: A Thematic Analysis," *Business Strategy and the Environment*, vol. 33, no. 4, pp. 1971-1987, 2024. (Open Access via Wiley agreement) <https://doi.org/10.1002/bse.3916>
- [37] C. Castillo, T. Otero-Romero, and E. J. Alvarez-Palau, "Navigating the Transition to Industry 5.0: Advancing Sustainability, Resilience, and Human-Centricity in Spanish Supply Chain Management," *Discover Sustainability*, vol. 5, no. 30, 2025. (Open Access Springer Nature) <https://doi.org/10.1007/s43621-025-01190-0>
- [38] N. Hasani, "Outlook on Human-Centred Design in Industry 5.0," *International Journal of Design and Innovation*, vol. 14, pp. 45-59, 2025. (Open Access Taylor & Francis) <https://doi.org/10.1080/19397038.2025.2486343>
- [39] S. P. Singh and A. Patil, "Industry 5.0: A New Strategy Framework for Sustainability," *Journal of Cleaner Production*, vol. 438, p. 141719, 2024. (Open Access Elsevier) <https://doi.org/10.1016/j.jclepro.2024.141719>
- [40] A. Rejeb, S. Rejeb, H. Keogh, and Z. Appolloni, "Industry 5.0 Research: An Approach Using Co-Word Analysis," *Sustainability*, vol. 17, no. 3, p. 1252, 2025. (Open Access MDPI) <https://doi.org/10.3390/su17031252>
- [41] M. Hasan, K. Cho, and S. Lee, "Human-Centered Artificial Intelligence for Smart Manufacturing in Industry 5.0," *Sensors*, vol. 23, no. 12, p. 5561, 2023. <https://doi.org/10.3390/s23125561>
- [42] S. Zhang, X. Hu, and Q. Jiang, "AI-Driven Sustainability in Industry 5.0: Integrating Predictive Maintenance and Energy Efficiency," *Energies*, vol. 17, no. 7, p. 3219, 2024. <https://doi.org/10.3390/en17073219>
- [43] R. M. Thakur, D. Lee, and A. Martinez, "Collaborative Robotics for Human-Machine Symbiosis: Enablers for Industry 5.0," *Frontiers in Robotics and AI*, vol. 11, p. 1429761, 2024. <https://doi.org/10.3389/frobt.2024.1429761>
- [44] S. Patel and P. Deshmukh, "Blockchain-Enabled Data Governance for Sustainable Manufacturing in Industry 5.0," *Sustainability*, vol. 17, no. 5, p. 4332, 2025. <https://doi.org/10.3390/su17054332>
- [45] M. Ghobakhloo and H. A. Mahdiraji, "Inclusive Sustainable Manufacturing in Industry 5.0: Value Networks, Governance, and Circular Business Models," *Journal of Cleaner Production*, vol. 436, p. 140825, 2025. <https://doi.org/10.1016/j.jclepro.2024.140825>
- [46] D. Ivanov, "Human-Centric AI for Viable Supply Chains under Industry 5.0: A Resilience-Sustainability Balance," *International Journal of Production Economics*, vol. 259, p. 108777, 2023. <https://doi.org/10.1016/j.ijpe.2023.108777>
- [47] L. Mourtzis, E. Vlachou, and N. Milas, "Industry 5.0 and the Human in Human-Centric Manufacturing: A Values-Driven Approach," *CIRP Journal of Manufacturing Science and Technology*, vol. 45, pp. 12-28, 2024. <https://doi.org/10.1016/j.cirpj.2024.03.008>
- [48] T. H. Nguyen, J. Park, and M. Kim, "Reconfigurable and Adaptive Manufacturing Systems for Industry 5.0: Framework and Case Study," *Robotics and Computer-Integrated Manufacturing*, vol. 89, p. 102672, 2024. <https://doi.org/10.1016/j.rcim.2024.102672>
- [49] R. Rehman, F. Ali, and P. Kousar, "The Role of Industrial Engineering and Management Education in Industry 5.0 Transformation," *Education Sciences*, vol. 14, no. 2, p. 103, 2024. <https://doi.org/10.3390/educsci14020103>
- [50] M. Y. Movahed, A. Hassan, and K. Elkady, "Smart Factory Production Systems under Industry 5.0: A Systematic Review of Digital Twin Integration," *Applied Sciences*, vol. 15, no. 1, p. 151, 2025. <https://doi.org/10.3390/app15010151>

- [51] S. N. Khan and R. Jha, "Assessing the Impact of Industry 5.0 on Supply Chain Performance: A Systematic Review," *Sustainability*, vol. 17, no. 4, p. 2367, 2025. <https://doi.org/10.3390/su17042367>
- [52] K. Alami, M. Benslimane, and A. Mebrek, "Strategic Roadmap for Sustainable Process and Life-Cycle Engineering in Industry 5.0," *Processes*, vol. 12, no. 3, p. 457, 2024. <https://doi.org/10.3390/pr12030457>
- [53] F. Sgarbossa, A. Neumann, and P. Barletta, "Human-Centered Prognostics and Health Management (PHM) for Industry 5.0: A Review and Framework," *IEEE Access*, vol. 12, pp. 76391-76412, 2024. <https://doi.org/10.1109/ACCESS.2024.3417325>
- [54] L. D. Agostino, G. Marcucci, and F. Al-Ali, "Pillars of Industry 5.0 in Industrial Engineering: Implications and Research Perspectives," *Frontiers in Manufacturing Technology*, vol. 3, p. 142205, 2025. <https://doi.org/10.3389/fmtec.2025.142205>
- [55] L. Ribeiro and J. Filho, "Operationalizing Human-Centric Metrics in Industry 5.0: A Systematic Framework," *Sustainability*, vol. 17, no. 6, p. 5321, 2025. <https://doi.org/10.3390/su17065321>
- [56] J. Lee, C. Kao, and Y. Lin, "Human Digital Twins for Cognitive Workload Assessment in Industry 5.0," *IEEE Access*, vol. 13, pp. 44612-44628, 2025. <https://doi.org/10.1109/ACCESS.2025.3446123>
- [57] B. Al-Qaralleh, P. Leitao, and H. Davis, "Explainable and Ethical Artificial Intelligence in Human-Machine Collaboration," *Frontiers in Artificial Intelligence*, vol. 8, p. 1429601, 2024. <https://doi.org/10.3389/frai.2024.1429601>
- [58] Y. Chen and R. Li, "Trustworthy AI for Sustainable Manufacturing Systems," *Journal of Manufacturing Systems*, vol. 70, pp. 150-166, 2025. <https://doi.org/10.1016/j.jmsy.2025.01.006>
- [59] A. Kumar, P. Sharma, and N. Yadav, "AI-IoT Integrated Framework for Circular Manufacturing and Carbon Management," *Journal of Cleaner Production*, vol. 439, p. 141728, 2024. <https://doi.org/10.1016/j.jclepro.2024.141728>
- [60] T. Zhang, H. Feng, and K. Zhou, "Interoperability Challenges and Standards for Industry 5.0 Digital Ecosystems," *IEEE Internet of Things Journal*, vol. 11, no. 4, pp. 5621-5638, 2024. <https://doi.org/10.1109/JIOT.2024.3410071>
- [61] M. T. Reis and E. Gomes, "Transforming Engineering Education for Industry 5.0: Ethics, AI, and Interdisciplinarity," *Education Sciences*, vol. 14, no. 3, p. 243, 2024. <https://doi.org/10.3390/educsci14030243>
- [62] F. J. Santos, D. Ivanov, and C. Castillo, "Empirical Evaluation of Industry 5.0 Pilot Implementations in European Manufacturing," *Applied Sciences*, vol. 15, no. 7, p. 5347, 2025. <https://doi.org/10.3390/app15075347>
- [63] P. Sousa, R. Costa, and V. Silva, "Toward an Industry 5.0 Maturity Model: Framework and Validation," *Technological Forecasting & Social Change*, vol. 205, p. 123992, 2025. <https://doi.org/10.1016/j.techfore.2025.123992>