Reimagining Industrial Leadership in the Era of Industry 5.0: Human-Centred Engineering, Digital Transformation, and Sustainable Manufacturing Performance.

Abstract

Industry 5.0 asks manufacturers to place human well-being, resilience and sustainability alongside efficiency as goals of digital transformation. Whether that ambition changes how factories are designed and led, or remains a policy label attached to familiar technologies, is an open question. This review examines what Industry 5.0 means for industrial leadership, drawing together evidence on human-centred engineering, digital transformation and sustainable manufacturing performance. A systematic integrative approach was applied to 30 journal studies dated 2020 to 2025, anchored by a systematic review asking whether Industry 5.0 is genuinely human-centred and an interview study of the transition to Industry 5.0 in Spanish supply chain management. The corpus spans reviews, interview and case research, surveys with structural modelling, laboratory and field experiments, and system design studies. Four findings emerge. First, the human-centred turn is real in policy and research agendas, yet implementation remains largely techno-centred and the voice of workers is often missing from engineering practice. Second, human-centred engineering at the workstation, including collaborative robots, ergonomic monitoring, human digital twins, exoskeletons and augmented reality, can reduce physical and cognitive strain and support skill development, but outcomes depend on the mode of interaction, workstation design and acceptance. Third, digital and Industry 5.0 capabilities are associated with sustainable performance, with circular practices, green innovation and digital leadership acting as mediators or moderators. Fourth, leadership, culture and workforce engagement are the decisive enablers and their absence the main barrier. The paper proposes a four-role model of human-centred industrial leadership and a human–machine interaction ladder, and outlines a research agenda.

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1. Introduction

For most of the past decade, the digital transformation of manufacturing was framed by Industry 4.0: connected machines, data analytics, automation and cyber-physical systems, adopted mainly

to raise efficiency and flexibility. Industry 5.0 reframes the same technological base around three values, human-centricity, resilience and sustainability, placing the worker at the centre of production and giving priority to well-being together with more sustainable and resilient systems (Alves et al., 2023). The shift is significant for industrial leaders, because it changes what counts as success. A factory that is highly automated but unsafe, exclusionary or environmentally damaging would not meet the standard Industry 5.0 sets.

The reframing has attracted rapid scholarly attention. A bibliometric analysis of 300 publications found that most research on Industry 5.0 appeared between 2020 and 2023, with sustainable development, human-centricity and smart manufacturing among its most frequent concepts (Ben Youssef & Mejri, 2023). Yet attention does not guarantee substance. Reviews of how the human operator is represented in digital manufacturing find that a techno-centred approach still dominates implementation and that social dimensions of work are treated as residual issues (Cunha et al., 2022). If Industry 5.0 is to be more than a relabelling of Industry 4.0, it requires changes in how systems are engineered and how organisations are led.

Leadership is where these changes converge. Engineers decide how collaborative robots, sensors and digital twins are configured; managers decide whether workers are consulted, retrained or replaced; executives decide whether social and environmental outcomes are measured alongside output. Recent interview evidence identifies proactive leadership and leadership-driven cultural change as key enablers of the transition to Industry 5.0, and resistance to change and financial constraints as critical barriers (Castillo et al., 2025). What remains unclear is what such leadership involves in practice, how it relates to the engineering of human-centred work systems, and how it connects with sustainable manufacturing performance.

This review addresses that gap. It synthesises research on the meaning of Industry 5.0, on human-centred engineering at the level of the workstation and production system, and on the links among digital capabilities, leadership and sustainable performance. Its contribution is to move the discussion of Industry 5.0 leadership from aspiration to mechanism, by identifying what the evidence shows about specific interventions and enabling conditions and by organising those findings into a model of leadership roles and a staged view of human–machine interaction.

The research questions are stated in Section 2 and the review procedure in Section 3. Section 4 examines the human-centred turn and the gap between rhetoric and practice. Section 5 reviews

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human-centred engineering interventions. Section 6 analyses leadership, capabilities and sustainable performance, and presents the integrated model. Implications, an agenda for further work and the limits of the review are considered in Section 7, before Section 8 offers concluding reflections.

2. Aim, Objectives and Research Questions

The study has a twofold purpose: to clarify how industrial leadership must change if the human-centred, resilient and sustainable goals of Industry 5.0 are to be realised, and to establish what evidence exists on the engineering and organisational means of achieving them. Four objectives follow: (1) to assess how far research and practice have moved from techno-centred towards human-centred manufacturing; (2) to evaluate the human and operational outcomes of human-centred engineering interventions; (3) to examine how digital capabilities, leadership and workforce development relate to sustainable manufacturing performance; and (4) to integrate these findings into a model that can guide leaders and future research.

The synthesis is steered by three research questions. RQ1 asks how the human-centred principle of Industry 5.0 is understood in recent research and how far it is reflected in engineering and implementation practice. RQ2 asks what human-centred engineering interventions achieve for workers and for production performance, and which conditions shape those outcomes. RQ3 asks how leadership, capabilities and workforce development link digital transformation with sustainable manufacturing performance, and what roles this implies for industrial leaders. The three questions are addressed in Sections 4, 5 and 6 respectively.

3. Review Methodology

An integrative design was adopted because the relevant evidence comes from fields with different methods and assumptions: production engineering, ergonomics, human–robot interaction, operations management, organisational behaviour and sustainability. An integrative synthesis allows experimental results on cognitive workload to be read alongside surveys of sustainable performance and interviews with managers, while keeping the type and strength of each study's evidence visible.

Searches of a comprehensive scholarly metadata index were completed in November 2026. Query strings combined Industry 5.0 terms ("Industry 5.0", "human-centric manufacturing",

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"human-centred", "Operator 4.0") with terms for engineering interventions ("collaborative robots", "human–robot collaboration", "ergonomics", "human digital twin", "exoskeleton", "augmented reality", "cognitive workload"), for leadership and the workforce ("digital leadership", "leadership styles", "competencies", "skills", "acceptance") and for outcomes ("sustainable performance", "circular economy", "social sustainability").

Records qualified for inclusion when they were peer-reviewed journal articles in English, carried a version-of-record year from 2020 to 2025, concerned manufacturing or industrial supply chains, and offered empirical, experimental, design or review evidence relevant to any of the three questions. Conference papers, editorials and commentaries were excluded, as were articles whose metadata or abstracts could not be confirmed against their registered identifiers. Where several studies addressed the same intervention, preference went to those that reported human as well as operational outcomes.

Two studies anchored the selection. One is a systematic review examining whether Industry 5.0 genuinely puts people first and which of its technologies can make that happen (Alves et al., 2023). The other analyses 25 interviews with professionals about the transition to Industry 5.0 in Spanish supply chain management (Castillo et al., 2025). Of the 30 studies finally retained, ten are reviews, two are conceptual frameworks, four are interview or case studies, five are surveys or scale-development studies, one is a multi-criteria study, five are laboratory or field experiments and three are system or tool design studies.

Each study was coded for setting, method, intervention or construct, human outcomes, operational or sustainability outcomes, enabling conditions and stated limitations. Findings were compared within and across the three research questions, and convergent and conflicting results were noted. Quantitative results reported here are taken directly from the studies, and no additional data were generated.

4. The Human-Centred Turn: From Principle to Practice

At the level of principle, the human-centred turn is clear. Industry 5.0 puts people at the heart of production, prioritises worker well-being and seeks to empower operators to improve their skills in collaboration or cooperation with digital technologies such as artificial intelligence, robotics and human–robot collaboration (Alves et al., 2023). Frameworks for sustainable manufacturing

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now use Industry 5.0 values to guide the selection of enabling technologies across economic, social and environmental dimensions, partly to prevent a widening digital divide among vulnerable workers (Martín-Gómez et al., 2024). A survey of manufacturing types argues that agile, holonic, flexible and reconfigurable systems can all benefit from Industry 5.0's emphasis on people and that life cycle analysis should guide decisions presented to people through digital twin visualisation (Turner & Oyekan, 2023).

At the level of engineering practice, the picture is more mixed. A systematic review combining disciplinary perspectives found evidence of a human-centric approach in practice-focused engineering papers: employees are highly valued as end users of innovative systems, and more research now models human activity. However, the same review found that efforts to increase manufacturing effectiveness often neglect worker voice (Briken et al., 2023). Workers are designed for more often than they are designed with.

Research on the Operator 4.0 reinforces this concern. A systematic review concluded that a techno-centred approach still guides implementation, that social dimensions of work remain residual issues overshadowed by promises of productivity and efficiency, and that the operator is represented as gender-neutral, skilful and perfectly fit for work. When work is examined as it is actually carried out, questions of employment conditions, new risks and effects on health come to the fore (Cunha et al., 2022). Inclusion is a further test. A review of 69 publications on workstations for operators with disabilities found that people with disabilities remain largely excluded from manufacturing, that Industry 4.0 technology lacks social applicability, and that few studies connect workstation design with disability, sustainability and the goals of Industry 5.0 (Bonello et al., 2023).

For smaller firms, the transition involves technological, social and organisational adaptation together. Expert interviews in Germany, Slovakia and South Africa, interpreted through a human–technology–organisation model, identified challenges of workforce availability, regulatory change, institutional cooperation and technological advancement, with regional differences with data privacy weighing more heavily in the European cases and skill shortages in the South African one (Zincume & Maier, 2025). In Spanish supply chains, resistance to change, limited finance and misalignment across sectors proved to be critical barriers, particularly for small and medium-sized enterprises (Castillo et al., 2025).

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The answer to RQ1 is therefore that the human-centred principle is well articulated in research and policy but only partially realised in engineering and implementation. Human-centricity is commonly understood as worker well-being, skill empowerment and inclusion, combined with resilience and sustainability. In practice, human factors are increasingly modelled, but workers' own perspectives are often absent, inclusion is rarely addressed, and smaller firms face structural barriers to change. Closing this gap is primarily a leadership task, because it requires decisions about whose needs shape system design.

5. Human-Centred Engineering at the Workstation

Collaborative robots are the emblematic Industry 5.0 technology, but their effect on work depends on how they are used. Qualitative research based on reports covering 200 cobots in 138 companies, interviews and a six-month follow-up in a manufacturing plant distinguished four modes of interaction between people and cobots, rising from coexistence and synchronism to cooperation and, finally, full collaboration. Most companies were at early stages of implementation and focused on substituting workers. Effects ranged from deskilling to reskilling depending on the activity, and upskilling was most evident in the more advanced modes of interaction, regardless of company size (Dornelles et al., 2023). The finding places a leadership choice at the centre of cobot deployment: the same technology can erode or build skills depending on the interaction mode managers select.

Acceptance shapes whether collaboration succeeds. Interviews with 17 assembly workers in four companies found that some saw human–robot collaboration as a threat and others as an opportunity, depending on their thoughts and feelings about both the robot and the organisational change accompanying it; robot-related, individual and organisational factors all played a part (Meissner et al., 2021). Design features matter too. In a factorial experiment with 40 participants, the type of cobot and the presence of a screen affected trustworthiness, perceived risk and the attention required (Liu et al., 2024). In a study of cognitive workload across three workstation configurations, workload fell across trials, and user acceptance predicted perceived stress, whereas trust did not moderate the link between workload and stress (Panchetti et al., 2023). For smaller firms that lack coherent acceptance strategies, a web-based tool for estimating employee acceptance was judged beneficial by three German enterprises because it raised awareness of the issue (Baumgartner et al., 2022).

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Ergonomics can be designed into production systems rather than added afterwards. A genetic algorithm for assembly line balancing that included job rotation and human–robot collaboration minimised both the cost of the line and the variance of energy load among workers, and was applied to an industrial assembly case (Dalle Mura & Dini, 2022). An adaptive framework combining visual perception, continuous ergonomic monitoring and behaviour-tree decision-making had the robot assist only when real-time assessment indicated hazardous postures, keeping 97.4% of operations human-led in laboratory validation, with decision latency about 56% faster than a representative earlier controller (Iodice et al., 2025). Both studies treat human well-being as an explicit objective of system design.

Digitising the human factor extends this approach. A digital architecture combining a smart glove, marker-less cameras and surface electromyography computed ergonomic risk indicators within a decision support system, and was validated in a pilot environment where an operator assembled furniture; the authors present it as a means to protect an ageing workforce and support inclusive workplaces (Tomelleri et al., 2024). Human digital twins, digital replicas that mirror human characteristics in system design and performance, are a fast-evolving field whose frameworks, enabling technologies and development challenges have been reviewed (Bucci et al., 2024). A conceptual framework goes further, proposing to monitor physical, mental and emotional states through natural language processing, facial and speech analysis and personality tests; its authors acknowledge that it has not been applied in a real setting (Davila-Gonzalez & Martin, 2024). Such proposals raise questions of privacy and consent that leaders must address before deployment.

Physical and cognitive assistance technologies show benefits with caveats. In a textile factory, eight workers using a passive arm-support exoskeleton for overhead tasks reported a 46% reduction in perceived effort and high satisfaction and usability, although long-term effects remain to be studied (Capodaglio et al., 2024). In maintenance and assembly tasks, augmented reality instructions reduced task time compared with paper instructions, by 14.94% for highly demanding tasks, while increasing mental workload, which the authors linked to greater germane cognitive load and potential for learning (Alessa et al., 2023). A review of extended reality in manufacturing found augmented and virtual reality widely adopted for design, quality control

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and maintenance, and proposed a roadmap while noting barriers to wider adoption (Egbengwu et al., 2025).

In answer to RQ2, human-centred engineering interventions can reduce physical strain, support skill development and maintain human control while improving efficiency. Table 1 summarises the main results. Three conditions shape outcomes: the mode of human–machine interaction, which determines whether skills are eroded or built; workstation and interface design, which affects workload, trust and perceived risk; and acceptance, which depends on how workers perceive both the technology and the organisational change around it. Much of the evidence comes from laboratory settings, pilots and small samples, so effects at scale remain to be confirmed.

Table 1. Human-centred engineering interventions: settings and reported outcomes

Study	Intervention	Setting and method	Human outcome	Operational outcome
Dornelles et al. (2023)	Cobots in four interaction modes	200 cobots in 138 firms; interviews; plant follow-up	Deskilling to upskilling, depending on mode	Most firms focused on substitution
Panchetti et al. (2023)	Workstation and interaction redesign	Assembly task in three scenarios	Workload fell; acceptance predicted stress	Insights for collaborative assembly design
Liu et al. (2024)	Cobot type and screen	Factorial experiment, 40 participants	Form affected trust, perceived risk and attention	Implications for cobot design and training
Dalle Mura and Dini (2022)	Job rotation and collaboration in line balancing	Genetic algorithm; industrial case	Smoother energy load among workers	Line cost minimised
Iodice et al. (2025)	Ergonomics-driven adaptive assistance	Laboratory validation	97.4% of operations human-led	Decision latency about 56% faster
Tomelleri et al. (2024)	Digital ergonomic assessment	Sensors in a pilot assembly environment	Ergonomic risk indicators for operators	Decision support for process weaknesses
Capodaglio et al. (2024)	Passive arm-support exoskeleton	Textile factory, eight workers	46% lower perceived effort; high satisfaction	Long-term effects untested
Alessa et al. (2023)	Augmented reality instructions	Maintenance and assembly experiment	Higher mental workload; learning potential	Task time 14.94% lower for demanding tasks

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6. Leadership, Capabilities and Sustainable Manufacturing Performance

Survey evidence links digital capabilities with sustainable performance, typically through intermediate practices. Among 179 respondents in Chinese manufacturing, Industry 5.0 technological capabilities, covering artificial intelligence, big data analytics, the Internet of Things, machine learning and blockchain, directly affected environmental, social and economic performance, and circular economy practices played both mediating and moderating roles (Shafique et al., 2024). In Indian automotive component manufacturing, structural modelling showed that Industry 4.0 technologies were closely tied to sustainable manufacturing practices, and that together they shaped organisational sustainable performance across all three dimensions (Harikannan et al., 2025). A review of 33 studies on manufacturing SMEs identified Industry 4.0 competencies relevant to sustainable manufacturing performance and proposed rational culture as a potential moderator (Yeo & Ong, 2024).

Leadership appears in this evidence as a moderator and an enabler. In a survey of 299 employees in Pakistani manufacturing firms, innovation capabilities and green process innovation were significantly related to sustainable performance, green product innovation mediated these links, and digital leadership strengthened employees' creative skills and sustainable performance (Sarfraz et al., 2022). In steel manufacturing, a framework built from a literature review and validated with professionals ranked top management commitment first among environmental criteria and employee satisfaction first among social criteria (Lahri et al., 2025). In Spanish supply chains, proactive leadership, circular economy integration and customised digitalisation strategies were the main enablers of the transition, and human–machine collaboration and digitalisation acted as catalysts for both sustainability and resilience (Castillo et al., 2025).

Leadership style influences how employees experience change. A survey study of manufacturing SMEs in the United Arab Emirates examined how far lean principles were understood and adopted and how different leadership styles affected employee performance during the lean transition (Alefari et al., 2020). The same concern applies to digital transformation more broadly. A validated self-assessment scale defines digital leadership through seven human-centric dimensions, among them a participative style, a transparent agenda, a growth mindset, ethical use of artificial intelligence and continuing skills acquisition (Abbu et al., 2025). Its emphasis on ethics, transparency and participation is consistent with the values Industry 5.0 promotes.

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Workforce capability is the other side of leadership. A bibliometric analysis of 80 papers on skills for digital industry in France identified six interconnected skill domains, ranging from technical and information technology skills to flexibility, inter-agency working, soft skills and innovation, and argued for development strategies that integrate technical and interpersonal skills (Turcato et al., 2024). Combined with evidence that advanced modes of cobot interaction build skills while substitution erodes them (Dornelles et al., 2023), this suggests that leaders shape skill trajectories through technology choices as well as training budgets.

Figure 1 integrates these findings into a four-role model of human-centred industrial leadership. As steward of well-being, the leader makes physical, cognitive and psychological health an explicit design and performance objective, drawing on ergonomic monitoring and assistance technologies. As architect of human–machine systems, the leader chooses interaction modes, workstation designs and interfaces that keep people in control and build their skills. As developer of capabilities, the leader invests in integrated technical and interpersonal skills and in the acceptance and participation of workers. As integrator of sustainability, the leader connects digital capabilities with circular and green practices and with social as well as environmental measures of performance. Table 2 links each role to practices, indicators and supporting evidence.

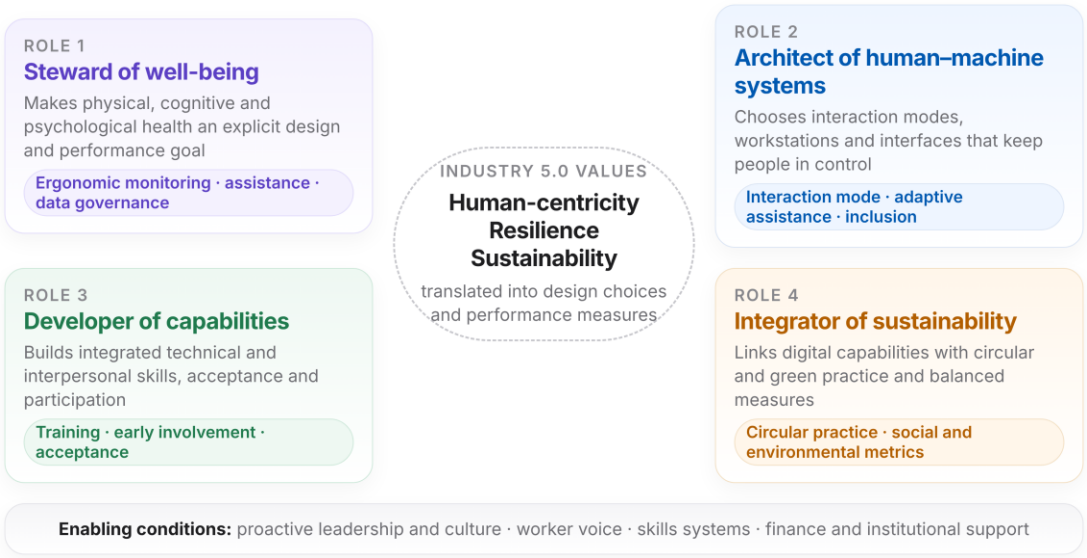


Figure 1. A four-role model of human-centred industrial leadership for Industry 5.0.

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Figure 2 presents a human–machine interaction ladder derived from the four modes of human–cobot interaction (Dornelles et al., 2023). At the lower rungs, coexistence and synchronism, robots and people share space or sequence but not tasks, and implementations often aim at substitution. At the upper rungs, cooperation and collaboration, people and robots work on shared tasks, and upskilling becomes more likely. Each rung calls for different leadership attention: acceptance and safety at the lower levels, and skill development, ergonomic design and adaptive assistance at the higher ones. Moving up the ladder is a strategic decision rather than a technical inevitability.

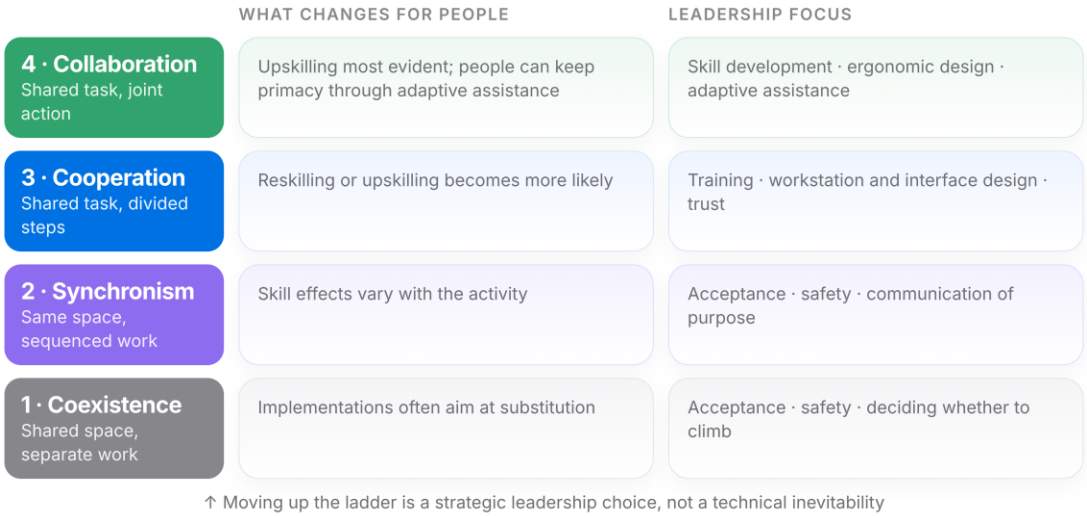


Figure 2. The human–machine interaction ladder and the leadership focus at each level.

In answer to RQ3, leadership links digital transformation with sustainable manufacturing performance in three ways: by committing the organisation to social and environmental objectives, by moderating how digital and innovation capabilities translate into sustainable performance, and by shaping the culture, acceptance and skills on which human-centred systems depend. These functions imply four complementary roles, through which leaders turn the values of Industry 5.0 into design choices and performance measures.

Table 2. A four-role model of human-centred industrial leadership

Leadership role	Focus	Illustrative practices	Indicators	Supporting evidence
Steward of well-being	Physical, cognitive and psychological health	Ergonomic monitoring; assistance technologies; data governance	Ergonomic risk; workload; perceived effort	Tomelleri et al. (2024); Capodaglio et al. (2024)

Leadership role	Focus	Illustrative practices	Indicators	Supporting evidence
Architect of human–machine systems	Interaction modes, workstations and interfaces	Select higher interaction modes; adaptive assistance; inclusive design	Share of human-led tasks; trust; acceptance	Dornelles et al. (2023); Iodice et al. (2025)
Developer of capabilities	Skills, acceptance and participation	Integrated technical and interpersonal training; early involvement	Skills profiles; acceptance; participation	Turcato et al. (2024); Meissner et al. (2021)
Integrator of sustainability	Linking digital capabilities to social and environmental results	Circular and green practices; balanced performance measures	Environmental, social and economic performance	Shafique et al. (2024); Sarfraz et al. (2022)

7. Discussion, Research Agenda and Limitations

The central implication of the review is that Industry 5.0 relocates the main challenge of digital transformation from technology to leadership. The technologies associated with Industry 5.0 largely already exist; what distinguishes a human-centred implementation is the set of choices made about interaction modes, design objectives, worker participation and performance measures. The evidence that most cobot implementations focus on substitution (Dornelles et al., 2023), that engineering papers often neglect worker voice (Briken et al., 2023) and that techno-centred approaches still dominate (Cunha et al., 2022) suggests that these choices are frequently made by default rather than by design.

A second implication concerns performance. The survey evidence that digital and Industry 5.0 capabilities are associated with sustainable performance (Harikannan et al., 2025; Shafique et al., 2024) is encouraging but rests on cross-sectional self-reports and rarely measures human outcomes directly. The engineering studies, by contrast, measure human outcomes such as workload, effort and ergonomic risk precisely, but in small samples and controlled settings (Alessa et al., 2023; Capodaglio et al., 2024; Iodice et al., 2025). The two literatures need to be joined, so that firm-level studies include validated measures of well-being and skills, and engineering studies follow interventions into sustained production.

There is also a tension that leaders must manage. The technologies that make human-centricity measurable, such as sensors, electromyography, emotion recognition and human digital twins, also intensify monitoring of workers (Davila-Gonzalez & Martin, 2024; Tomelleri et al., 2024). Without clear governance of consent, data use and purpose, tools designed to protect workers

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could be experienced as surveillance and undermine the trust and acceptance on which collaboration depends (Meissner et al., 2021).

Practitioners can draw four lessons. Treat worker well-being and skill development as design objectives with explicit indicators, alongside cost and throughput. Choose higher interaction modes where tasks allow, and pair them with training and ergonomic design. Involve workers early, assessing acceptance and addressing concerns about organisational change as well as technology. Measure sustainable performance in social as well as environmental and economic terms, and link digital investment to circular and green practices.

The research agenda follows from the gaps. Longitudinal field studies are needed to test whether human-centred interventions sustain their benefits for workers and performance. Validated instruments for human-centred leadership, building on the digital leadership scale (Abbu et al., 2025), should be tested in manufacturing and linked to measured outcomes. The inclusion of workers with disabilities and older workers deserves systematic attention (Bonello et al., 2023; Tomelleri et al., 2024). Comparative research across regions, as begun by Zincume and Maier (2025), should examine how institutions and skills systems shape the transition for smaller firms. Finally, the ethics and governance of human monitoring in manufacturing require dedicated study.

The review has limitations. Thirty studies cannot capture the full breadth of a fast-growing literature, and conference proceedings, which are prominent in this field, were excluded. Several survey studies come from single countries and sectors, and many engineering results come from laboratory or pilot settings with small samples. Where full texts were unavailable, claims rest on abstracts. Selection and coding were performed by a single reviewer, and the leadership model and interaction ladder are interpretive syntheses that require empirical testing.

8. Conclusion

Industry 5.0 promises a manufacturing sector in which technology serves people, resilience and the environment as well as efficiency. The evidence reviewed here shows that the promise is well articulated but unevenly realised. Human-centred engineering interventions can reduce strain, build skills and preserve human control, and digital capabilities are associated with sustainable performance, but the outcomes depend on choices that are made by leaders.

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Reimagining industrial leadership for Industry 5.0 therefore means accepting responsibility for those choices. The four roles proposed here, steward of well-being, architect of human–machine systems, developer of capabilities and integrator of sustainability, describe what that responsibility involves. Leaders who exercise these roles deliberately, and who measure success in human and environmental as well as economic terms, are best placed to turn digital transformation into manufacturing that is both productive and worthy of the people who work in it.

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