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Towards Industry 5.0: A Conceptual Model for Leading Organisational Change in Digital Age

Abstract

Purpose: This study develops a theoretically grounded understanding of Industry 5.0 (IR5) and proposes an integrative framework to clarify its organisational implications for leading change in digitally transforming socio-technical environments.

Design/methodology/approach: The study employs a structured integrative review of 160 peer-reviewed articles and 7 institutional reports, guided by Socio-technical Systems Theory, to inform the analysis.

Findings: This study offers a new, concise definition of Industry 5.0 (IR5) as a socially constructed framework that reconfigures industrial systems by embedding the principles of human-centricity, sustainability, and resilience into advanced digitalisation. It introduces the IR5 CPC model (Conditions-Processes-Consequences), a comprehensive framework identifying key enabling conditions (e.g., visionary leadership, digital readiness), three digitalisation logics (resilience, sustainability, and well-being-driven), and dual outcomes (benefits and risks) across organisational, economic, societal, and environmental domains.

Research limitations/implications: This study encourages empirical research on how AI- and ERP-based (Enterprise Resource Planning) standard operating procedures (SOPs) facilitate IR5-aligned transformation. It also recommends multi-theoretical approaches to capture its socio-technical complexity.

Practical implications: This study facilitates change leaders in designing phased, ethically aware digital strategies and supports policymakers in aligning incentives and regulations with sustainable, inclusive digitalisation.

Originality/value: This is the first study to provide a theoretically integrated definition and framework of IR5, bridging fragmented literature and advancing future inquiry.

Keywords: Industry 5.0; digital transformation; contextual conditions; digitalisation process; consequences.

1 INTRODUCTION

In response to growing concerns about the unintended consequences of rapid technological advancement, a new vision for industry is emerging: Industry 5.0 (IR5). This paradigm, promoted by the European Commission (2021b), advances the Fifth Industrial Revolution by integrating cutting-edge digital technologies with three foundational principles: human centricity, environmental sustainability, and resilience. IR5 builds upon but seeks to transcend the technological priorities of the Fourth Industrial Revolution (IR4).

Coined in the early 2010s, Industry 4.0 signalled a shift in industrial organisation through the deployment of cyber-physical systems, the Internet of Things (IoT), cloud computing, and artificial intelligence (AI) in industrial processes (European Parliament, 2016). It emphasised automation, real-time data, and machine interconnectivity to enhance productivity and operational efficiency. However, despite its transformative potential, IR4 has been criticised for its technocratic orientation, often prioritising optimisation over human wellbeing, social inclusion, and ecological responsibility (European Commission, 2021b). These limitations have spurred interest in IR5, which reframes digitalisation as a tool to serve broader societal goals.

Regardless of terminological shifts, the integration of digital technologies continues to reshape how firms innovate, coordinate, and compete (Teece, 1998). Technologies such as AI, digital twins, and IoT have become central to business operations, enhancing agility, product development, and data-driven decision-making. However, these benefits are unevenly distributed and often contested. While some firms achieve efficiency gains, others encounter unintended consequences such as digital surveillance, workforce disruption, and environmental burdens (European Commission, 2021b; Filatotchev et al., 2025). This duality underscores that many organisations are still navigating IR4 while IR5 gains traction in strategic, policy, and academic discourses.

Against this backdrop, a growing body of research seeks to clarify the concept and implications of IR5 (Leng et al., 2022; Panagou et al., 2023), compare it with related paradigms (Bartoloni et al., 2022; Grabowska et al., 2022; Psarommatis et al., 2023; Tlili et al., 2023), and propose implementation roadmaps (Caiado et al., 2024; Enang et al., 2023; Piccarozzi et al., 2024). More recent reviews attempt to widen the analytical lens: Sneha & Kavitha (2024) explore IR5 within the creative economy, Panigrahi et al. (2025) examine inventory knowledge and performance, and Ali et al. (2025) synthesise 98 articles into a value-based framework. However, despite these contributions, much of IR5 literature remains fragmented across domains and under-theorised in relation to socio-technical change processes underpinning Industry 5.0. To date, no comprehensive framework captures the enabling conditions, transformation processes, and systemic consequences of IR5 in a unified way. A theoretically grounded and integrative understanding of IR5 is urgently needed to advance academic inquiry and inform strategic organisational change.

This study responds to this need by exploring four interrelated research questions: (i) What does Industry 5.0 mean? (ii) What conditions are needed to implement IR5? (iii) How can IR5 be implemented in practice? (iv) What are the potential organisational, economic, societal, and environmental impacts of IR5?

The study employs an integrative review method and critical analysis of 160 research articles published in high-quality journals ranked by the Chartered Association of Business Schools (CABS) and 7 policy reports by major international organisations.

This study makes three key theoretical contributions. ***First*****,** it offers a new, parsimonious definition of IR5 as a socially constructed framework that reconfigures industrial systems by embedding the principles of human-centricity, sustainability, and resilience into advanced digitalisation. This is the first academically grounded and theoretically integrated definition of IR5, moving beyond the policy-oriented framing of the European Commission to position IR5 as a value-driven innovation paradigm. It is accompanied by a comparative framework that distinguishes IR5 from earlier industrial revolutions, thereby contributing to debates on innovation systems and organisational change. ***Second*****,** it introduces the IR5 CPC (Conditions–Processes–Consequences) model, a comprehensive framework that captures how organisations engage with IR5, shaped by enabling conditions and yielding both benefits and risks. This framework advances change management theory by highlighting the tensions and trade-offs inherent in socio-technical transformation. ***Third*****,** the study contributes to theoretical integration by drawing on Socio-technical Systems Theory, the Capability Approach, Innovation Diffusion Theory, and Complexity Theory, providing a multidisciplinary foundation for future inquiry and organisational practice.

2 RELATED REVIEWS

Before conducting our in-depth analysis, we surveyed existing literature reviews on Industry 5.0 (IR5) to establish the current conceptual landscape in business and management scholarship. A systematic search of the Web of Science (Business and Management category) identified 15 relevant reviews published by June 2025.

Notably, a meta-level review by Jedynak et al. (2021) had already identified foundational gaps in the digital transformation literature, specifically, a lack of clarity around organisational enablers, change mechanisms, and long-term consequences. Our analysis of more recent IR5 reviews suggests that these gaps remain largely unresolved.

These reviews are thematically fragmented and vary in focus. Agrawal et al. (2023) examine IR5 technologies in mitigating supply chain disruptions from crises such as pandemics and climate change, but their scope is limited to resilience in supply chains. Coronado et al. (2022) explore human-robot interaction (HRI) in manufacturing, offering valuable metrics for human-centricity but confined to operational settings. Enang et al. (2023) apply a multi-level perspective to IR4–IR5 transitions, emphasising trust and autonomy but stopping short of exploring systemic consequences. Ghobakhloo et al. (2023) provide a sustainability roadmap and a definition of IR5, respectively, valuable contributions that nonetheless lack theoretical integration and level-spanning analysis.

Other reviews, such as Grabowska et al. (2022), adopt bibliometric methods to track themes like skill development and sustainability but remain descriptive. Leng et al. (2022) propose a tri-dimensional architecture grounded in the core principles of IR5 but do not explain the conditions or processes through which these are realised. Panagou et al. (2023) and Psarommatis et al. (2023) focus on micro-level HRI and maintenance frameworks within IR4, offering little insight into broader IR5 transformations. Similarly, Piccarozzi et al. (2024) and Tlili et al. (2023) discuss technology adoption and the metaverse as IR5 enablers, but their analyses are domain-specific and lack integrative synthesis.

More recent reviews by Sneha & Kavitha (2024), Panigrahi et al. (2025), and Ali et al. (2025) attempt to widen the lens. Sneha & Kavitha (2024) explore the intersection of IR5 and the creative economy, while Panigrahi et al. (2025) focus on inventory knowledge and firm performance in IR5 contexts, both offering unique angles but lacking theoretical depth. Ali et al. (2025) provide a broader synthesis across 98 articles and propose a framework grounded in IR5's core values, yet the analysis remains skewed towards Asia-Pacific and falls short of theoretical integration across organisational levels.

In sum, these reviews reflect a growing scholarly interest in IR5 but also reveal three consistent gaps: (i) fragmentation across domains and technologies, (ii) a lack of integrative theoretical grounding, and (iii) limited attention to contextual conditions and multi-level consequences.

Few reviews examine IR5 as a socio-technical transformation that bridges enabling conditions, organisational processes, and systemic impacts.

Our study addresses these limitations by offering the first CPC (Conditions-Processes-Consequences) model of IR5, supported by a multi-theoretical synthesis. This model provides a coherent framework to guide future research and practice, offering a comprehensive understanding of how IR5 is shaped by and shapes organisational change in business and society.

3 METHODOLOGY

To answer the research questions, we used an integrative literature review as a research methodology, following methodological insights from Elsbach & van Knippenberg (2020), Torraco (2005), and Cronin & George (2023). An integrative review approach enables the evolution of knowledge and theory development (Cronin & George, 2023).

3.1 Scope of review

To ensure comprehensive coverage and avoid omission of relevant studies, we employed a multi-stage search strategy comprising four components: (1) electronic database searching, (2) quality-based filtering, (3) backward and forward citation tracking, and (4) targeted grey literature screening.

First, we conducted a keyword search on the Web of Science database using the terms "Industry 5.0," "Industry 5," "I 5.0," "I 5," "IR5," and "IR5.0." The search was restricted to peer-reviewed journal articles published in English. Editorials, commentaries, and conference proceedings were excluded. *Second*, to ensure the quality and relevance of included studies, we filtered the initial results by retaining only those published in journals listed by CABS (2024). This yielded a preliminary sample of 147 peer-reviewed articles. *Third*, we conducted backward and forward citation tracking on this initial set to identify additional influential works that may not be indexed in CABS-listed journals but were frequently cited within the reviewed sample. This led to the inclusion of several additional sources, including books and book chapters, yielding a total of 160. *Fourth*, to capture key institutional contributions to the concept of Industry 5.0, we conducted targeted searches of websites from major international organisations, including the European Commission, United Nations, World Bank, IMF, ADB, and EBRD, using the same set of keywords. This ensured the inclusion of influential grey literature relevant to the policy framing and institutional development of IR5.

Our final sample comprises 160 academic publications and 7 policy documents. The complete list of reviewed articles and journal fields are available in the online appendix.

3.2 Analysis

We employed the structural content analysis approach proposed by Mayring (2014), which facilitates the systematic reduction of a large amount of text data from any document by classifying the information into unifying categories. We first focused on synthesising the concepts, definitions, and characteristics of IR5. We then adopted Pawson & Tilley (1997) basic design science logic, i.e., input-process-consequence structure, which allows an analysis of our collected data without preconceptions or prior assumptions. The structure is generic enough to scope the field and serve as a foundation for analysing the extensive and diverse literature on IR5. Within the input category, we identify conditions needed for the implementation of IR5, while in the consequence category, we focus on identifying the potential impacts of IR5. Our analytical framework aligns with that of Hanelt et al. (2021), a solid review and conceptual development of digital transformation, an essential part of IR4, paving the way for IR5 progress.

4 CONCEPTUALISATION OF INDUSTRY 5.0

For the conceptualisation of IR5, we draw from a sociological approach[1] (Giddens, 1993) that examines social phenomena through the lens of societal structures, institutional dynamics, and power relations. This perspective recognises that concepts and categories are socially constructed and reflect dominant ideologies. In this context, IR5 should not be understood merely as a technical innovation but as a socio-political construct shaped by institutional agendas and cultural narratives.

4.1 Definitions

Our content analysis of definitions provided in existing literature reveals significant efforts to conceptualise IR5. Table 1 summarises influential definitions found through cross-referencing our review sample and provides a critical analysis of each.

(Insert Table 1 here)

Table 2 outlines how major international organisations define IR5.

(Insert Table 2 here)

Most academic and institutional definitions of IR5 build on the European Commission's (2021b) framing, which integrates cyber-physical production systems (CPPS) with human intelligence and emphasises human-centricity, sustainability, and resilience. This framing has shaped international initiatives led by the United Nations, the IMF, the World Bank, the EBRD,

[1] Since Giddens's original work, the structuration perspective has been extended by scholars in organisation studies and technology research to explore how digital systems, innovation paradigms, and institutional logic co-evolve (Barley & Tolbert, 1997; Orlikowski, 2000; Sewell, 1992). While the core duality of structure and agency remains central, later contributions have integrated discursive, material, and practice-based dimensions of structuration into analyses of socio-technical change.

and the ADB, all of which have incorporated IR5 principles into their digital transition roadmaps (United Nations, 2022).

While this global uptake underscores the rising legitimacy of IR5, it also reflects normative alignment with the EU's digital strategy. As a result, dominant definitions often centre institutional perspectives and risk marginalising alternative, decentralised, or context-specific visions of industrial transformation. Although these definitions attempt to articulate a unified vision, they are embedded in institutional power structures that shape what is included or excluded in the narrative.

The emergence of IR5 as a distinct industrial paradigm invites critical questions. Why did the European Commission label it the "Fifth Industrial Revolution"? From a sociological standpoint, IR5 is a response to mounting societal pressures for industry to prioritise human wellbeing, sustainability, and resilience. This narrative responds to anxieties about automation, environmental degradation, and economic uncertainty. However, the alignment of IR5 with the EU's broader strategic interests, such as digital sovereignty and regulatory leadership, also suggests that IR5 is a tool for geopolitical positioning.

Notably, the construction of IR5 involves exclusions. While promoted as a human-centric alternative to IR4, its continued focus on advanced digitalisation and CPPS reveals a techno-centric bias. This orientation may overlook grassroots, community-driven, or low-tech pathways to sustainable industrial futures. Although regulatory initiatives like the General Data Protection Regulation (GDPR) and AI Act aim to embed ethical safeguards (European Commission, 2021a, 2021c), they remain technocratic in tone and often assume that governance mechanisms can resolve deeper societal tensions. For example, the emphasis on human-robot collaboration assumes seamless integration and overlooks issues like workforce resistance, skills gaps, and cultural frictions (Dignum, 2019).

From a sociological lens, the spread of the IR5 concept can also be viewed as a process of institutional diffusion. Academics and policymakers often echo the European Commission's framing, reinforcing its legitimacy. This raises questions about the mechanisms through which certain ideas gain prominence. Is the adoption of IR5 driven by its intrinsic utility, or does it reflect the influence of powerful actors and the alignment of the concept with prevailing institutional logic?

The definition of IR5 cannot be understood in isolation from the social and political context in which it was constructed. It represents not only a vision for the future of industry but also a strategic intervention shaped by the interplay of societal demands, institutional agendas, and technological imaginaries. Accordingly, ***we define IR5 as a socially constructed framework that reconfigures industrial systems by embedding the principles of human-centricity, sustainability, and resilience into advanced digitalisation.*** It emerges as a response to societal demands and institutional agendas addressing the challenges of automation, environmental crises, and systemic susceptibilities.

Rather than representing a linear evolution from IR4 or a purely technological shift at the firm level, IR5 is a strategic narrative that reflects dominant cultural and political values. It tends to favour high-tech, centralised models aligned with economic and geopolitical priorities while downplaying alternative development pathways. For example, the Fab City initiative promotes distributed, small-scale production using open-source tools (Diez, 2018), and movements like Transition Towns and Community-Supported Agriculture (CSA) highlight ecological sufficiency over productivity (Hopkins, 2008). Post-growth and degrowth scholarship further challenge the paradigm of endless industrial expansion by advocating for value systems rooted in care, circularity, and wellbeing (Jackson, 2016; Kallis et al., 2020; Latouche, 2009).

Our definition thus positions IR5 as a performative and contested category, shaped by institutional power, cultural logic, and systemic dissemination, that reflects and reproduces broader societal aspirations, anxieties, and inequalities.

4.2 Characteristics of Industry 5.0

The literature defines the unique characteristics of IR5 through its core principles of human-centricity, sustainability, and resilience (Asif et al., 2023; Ivanov, 2023; Xu et al., 2021). These three foundational attributes are widely understood as follows: (i) Human-centricity prioritises wellbeing, safety, autonomy, privacy, and growth opportunities in the workplace; (ii) Sustainability aligns economic growth with social and environmental progress through resource conservation and digital technologies; and (iii) Resilience is the ability to recover from disruptions by strengthening supply chains, systems, networks, and societal responses (Asif et al., 2023; European Commission, 2021b).

Framing these principles as solutions to contemporary global challenges, proponents of IR5 construct a narrative that aligns with dominant institutional logic and legitimises specific technological trajectories. This framing not only shapes the direction of digital industrial policy but also risks marginalising alternative visions rooted in local knowledge systems, low-tech innovation, or post-growth paradigms. Consequently, the characteristics of IR5 reflect a particular vision of industrial futures, one grounded in existing power structures and normative priorities.

4.2.1 Industry 5.0 as an evolution of previous industrial revolutions

IR5 is often positioned as a continuation and enhancement of earlier industrial revolutions. According to the European Commission (2021b), IR5 builds upon the technological foundations laid by Industry 4.0 (IR4), while introducing a stronger emphasis on societal well-being, sustainability, and resilience.

IR4, which emerged in the early 2010s, marked a shift in industrial organisation through the integration of advanced digital technologies into manufacturing and service processes. As defined by the European Parliament (2016), Industry 4.0 refers to the digital transformation of manufacturing through smart, interconnected systems enabled by cyber-physical systems, the Internet of Things (IoT), cloud computing, and artificial intelligence (AI). However, there is no globally standardised definition of Industry 4.0 issued by a body such as the International Organization for Standardization (ISO). Instead, IR4 has evolved through policy documents, industry initiatives, and academic debate, mainly originating in Germany's Industrie 4.0 platform. The essence of IR4 lies in the convergence of digital and industrial systems, revolutionising manufacturing and services through automation and data exchange. Despite significant gains in productivity and efficiency, IR4 has faced growing criticism for neglecting human and environmental dimensions, raising concerns about worker displacement, excessive resource consumption, and algorithmic bias.

IR5 seeks to correct these imbalances by embedding values such as sustainability, human wellbeing, and resilience into the design and governance of digital technologies. In doing so, IR5 reframes industrial progress as a value-driven process where technological innovation is aligned with broader societal and ecological objectives. To illustrate how IR5 builds on but departs from its predecessors, we present a comparative synthesis of key features across industrial revolutions in Table 3.

(Insert Table 3 here)

4.2.2 Technologies of Industry 5.0

Collaborative robots (cobots), AI, machine learning (ML), blockchain, IoT, and digital twins are widely recognised as core enablers of IR5 due to their role in supporting human-centric, sustainable, and resilient industrial systems (Asif et al., 2023). Cobots, for instance, can alleviate worker fatigue and assist with repetitive tasks (Maddikunta et al., 2022), yet they also raise questions about control, autonomy, and labour relations. Framing cobots purely as productivity tools risks overlooking underlying issues such as job insecurity, workplace surveillance, and decision-making asymmetries.

Similarly, AI and digital twins offer opportunities for operational efficiency, simulation, and real-time decision-making, but they are also associated with critical concerns over data privacy, algorithmic bias, and centralisation of power. Digital twins, in particular, can intensify employee monitoring, while AI systems, often perceived as neutral, may embed historical biases and reinforce structural inequalities.

Blockchain and IoT are often celebrated for promoting transparency and decentralisation. Nevertheless, in practice, blockchain's security protocols may consolidate authority within network managers, and IoT's pervasive connectivity may increase cyber vulnerabilities and raise concerns about data exploitation, especially among smaller firms with limited resources (Maddikunta et al., 2022).

Beyond these essential technologies, European Commission (2021b) identifies six strategic technology clusters for IR5 development: (i) "human-centric solutions" that combine technological tools with human capacities; (ii) "bio-inspired technologies" for recycling, sustainability, and circular economy transitions; (iii) "real-time digital twins" that replicate and analyse live processes; (iv) "cyber-secure interoperability" for safe data transmission across systems; (v) "artificial intelligence" for pattern detection and decision support in complex environments; and (vi) "technologies for energy efficiency and autonomous systems." Table 4 synthesises key digital technologies discussed in the literature and classifies them within these six categories.

(Insert Table 4 here)

4.2.3 Sociopolitical processes in industrial transitions

Each industrial revolution represents more than a technological upgrade; it also reshapes societal relations, labour dynamics, and cultural values. IR5's emphasis on human-centricity, sustainability, and resilience reflects widespread concerns about automation, environmental harm, and economic instability. These principles are not intrinsic to the technologies themselves but are shaped through sociopolitical processes, including institutional agendas, public discourse, and global competition (Perez, 2002).

IR5 extends the innovations of IR4 while framing itself as a corrective model that aims to generate social and environmental value. This framing legitimises IR5 as both a logical progression of industrial development and a necessary response to systemic crises. However, interpreting IR5 purely through its technical capabilities risks adopting a deterministic view that technologies inherently deliver societal benefit. A sociological perspective challenges this view, emphasising that technology adoption and use are shaped by power relations, cultural norms, and strategic interests (Barley & Tolbert, 1997; Orlikowski, 2000; Sewell, 1992; Garrod, 2016). For instance, while blockchain is often portrayed as democratising and decentralised, its real-world implementation can consolidate control among those who govern and maintain the system. This paradox underscores the need for critical inquiry into who gains and who loses from IR5 transformations (Ramirez, 2023).

4.2.4 Value creation: Economic vs. Social and Environmental

IR5's shift from purely economic value creation to the incorporation of social and environmental dimensions marks a major normative transition. The European Commission (2021b) advocates for production systems that respect ecological limits and human wellbeing, encouraging circular processes and inclusive design.

Emphasising resilience, IR5 addresses vulnerabilities revealed by global disruptions like the COVID-19 pandemic. However, resilience is often framed at the individual or organisational level rather than addressing the structural inequities that underpin vulnerability. A transformative approach must confront and correct these systemic imbalances (Ivanov, 2022).

Technological integration, such as with cobots, intends to enhance human roles, but studies suggest it can also entrench power disparities if workers lack a voice in design and deployment processes. Genuine human-centricity requires participatory mechanisms and inclusive design frameworks that incorporate workers' perspectives (Fraga-Lamas et al., 2022).

In sum, IR5 emerges at the intersection of technological advancement and sociopolitical context. Its success will depend not only on technical implementation but also on how equitably its benefits are distributed and how its risks are governed across diverse industrial and societal settings.

5 CONTEXTUAL CONDITIONS, PROCESSES AND CONSEQUENCES OF INDUSTRY 5.0

5.1 Contextual conditions

Contextual conditions refer to the organisational and environmental circumstances that influence the implementation of Industry 5.0 (IR5). These factors either enable or hinder firms in aligning with IR5's core values: human-centricity, sustainability, and resilience. We categorise them into two domains: organisational factors (e.g., visionary leadership, dynamic and inclusive organisational culture, and technological readiness) and environmental factors (e.g., digital literacy in the workforce, supportive economic and regulatory frameworks, and evolving societal expectations regarding ethical and responsible business conduct).

5.1.1 Visionary leadership

Leadership plays a pivotal role in translating IR5 principles into an actionable strategy. Moving beyond traditional goals of efficiency and productivity, IR5 demands a mindset shift that embraces human wellbeing, sustainability, and resilience as central tenets of value creation. Visionary leaders are those who can guide their teams with foresight, align technological initiatives with societal values, and navigate complex transformations decisively and ethically (Cillo et al., 2022; Grosse, 2024; Mukherjee et al., 2023).

Transformational leadership, where leaders inspire, motivate, and empower followers to exceed expectations and drive deep organisational change, also supports digital transformation by enhancing resilience and collaboration, as shown by Yang et al. (2025) during crisis contexts such as the COVID-19 pandemic. While distinct, visionary and transformational leadership share important overlaps in shaping strategic direction, fostering innovation, and enabling systemic change, which are core to IR5 implementation.

Such leadership is critical for fostering a culture of innovation and adaptability, as well as the conditions necessary for managing the human-machine interface and aligning digital technologies with broader stakeholder interests (Hooi & Chan, 2023). It also entails building inclusive, transparent environments where employees are empowered to co-create and contribute strategically. For instance, Khoshroo & Soltani (2025) demonstrate that in the tourism sector, effective IR5 adoption hinges on leadership that prioritises inclusivity, co-creation, and personalised engagement, highlighting the broader applicability of visionary leadership across diverse sectors embracing IR5.

5.1.2 Dynamic, agile and inclusive organisational culture

The evolving technological landscape of Industry 5.0 (IR5) demands that organisations continuously innovate and adapt. A dynamic organisational culture, one that fosters experimentation, learning, and responsiveness, is critical for the effective adoption and integration of emerging technologies (Erro-Garcés & Aramendia-Muneta, 2023; Scaliza et al., 2022). In contrast, rigid and hierarchical cultures often hinder progress in digitally transforming environments.

Agility complements dynamism by promoting responsiveness to uncertainty and continuous change. An agile culture encompasses shared values, beliefs, and practices that empower individuals and teams to adapt quickly, embrace innovation, and collaborate effectively. It fosters a mindset grounded in continuous improvement, cross-functional teamwork, and rapid iteration. These qualities are especially important given the organisational tensions that digitalisation often introduces. For instance, Lindell et al. (2022) highlight how employees navigating digitalised work environments face ideological dilemmas between structure and flexibility, underscoring the importance of agile organisational cultures that support self-regulation and adaptive behaviour. As Pfaff (2023) demonstrates, agility is a key success factor in mastering digitalisation and navigating complex socio-technical shifts.

Inclusivity further strengthens adaptive capacity. D'souza & Tapas (2024) introduce the concept of Diversity 5.0, arguing that inclusive practices enhance collaboration, organisational learning, and human-centric transformation. Diversity in perspectives and lived experiences unlocks creativity, improves problem-solving, and supports continuous renewal. This aligns with findings by Ullrich et al. (2023), who emphasise that successful digital transformation depends not just on the degree of employee involvement but on the context-specific selection and implementation quality of participative formats that empower employees as co-creators of change.

Taken together, a culture that is dynamic, agile, and inclusive not only enables successful technological adaptation but is foundational to advancing the broader goals of IR5, including resilience, sustainability, and human-centricity.

5.1.3 Technological readiness

To embark on the IR5 journey, firms must deploy essential enabling technologies and ensure robust digital infrastructure that supports interoperability across systems. The literature highlights that technologies such as cobots (Liao et al., 2023), AI (Ahmed et al., 2023), ML (El-Brawany et al., 2023), blockchain (Leng et al., 2023; Z.-J. Wang et al., 2023), IoT (Caiazzo et al., 2023), big data analytics (Hur et al., 2022), and digital twins (Cutrona et al., 2023) empower firms across sectors, from manufacturing and transport to healthcare, to realise IR5 outcomes. Narula et al. (2023) further emphasise that the implementation of IR5-enabling technologies such as AI, IoT, and robotics in manufacturing should be embedded within circular economy principles, underscoring the importance of aligning technological readiness with sustainable production systems. Festa et al. (2025) illustrate how AI-driven transformation in the wine industry advances customer experience, sustainability, and human-centric innovation, reinforcing how technological readiness can accelerate IR5-aligned outcomes. Latino (2025) also highlights the need for structured implementation models to assess technological maturity, particularly for guiding SMEs through staged digital transformation.

Beyond these technologies, digital infrastructure, including high-speed internet, cloud platforms, and cybersecurity, provides the foundational layer for integration (Wang et al., 2022). These infrastructures, shaped by both internal capabilities and external environments, are vital for data management, secure operations, and strategic digital (Karmaker et al., 2023; Kumar & Mallipeddi, 2022; Rani & Srivastava, 2024). Kerstens et al. (2024) further demonstrate that optimising IoT service delivery under IR5 requires not only robust infrastructure but also efficiency-driven technology configurations, reinforcing the need to align infrastructure with digital performance goals.

5.1.4 Digital literate workforce

The implementation of IR5 hinges on the availability of a digitally literate workforce capable of engaging with advanced technologies. At the firm level, employees must possess the digital skills required to operate and collaborate with intelligent systems. However, this organisational readiness depends significantly on broader systemic conditions, namely, the presence of national or industry-level education and training systems that cultivate digital literacy.

We identify two key domains of digital literacy essential for IR5: (i) data analytics skills, which enable workers to interpret and act upon data insights, and (ii) human-machine collaboration skills, such as operating cobots and engaging with AI-driven tools effectively. These capabilities are central to ensuring that employees can work alongside rather than be displaced by technological systems.

Ordieres-Meré et al. (2023) illustrate this through case studies of a steel rebar manufacturer and an automotive component supplier, where successful IR5 integration was contingent on human-machine co-working practices, including collaboration, coordination, communication, and joint decision-making. Their findings underscore that digital literacy extends beyond technical proficiency to encompass interactional and adaptive skills that are critical for co-evolution with machines in IR5 environments.

5.1.5 Economic and regulatory frameworks

A country's economic and regulatory landscape plays a vital role in shaping firms' strategies and determining the feasibility of IR5 implementation. Despite rising awareness, many firms continue to prioritise economic profitability over social and environmental concerns (Hein-Pensel et al., 2023). Regulatory incentives, funding programmes, and consumer demand for sustainable and personalised products are thus critical levers for aligning firm behaviour with IR5 principles.

Government intervention is a key enabler. For instance, Ghobakhloo, Iranmanesh, Morales, et al. (2023) highlight proactive public policy as foundational for enabling IR5 outcomes. Similarly, Pistolesi et al. (2024) demonstrate that manufacturers are more willing to invest in human-centric technologies when supported by public subsidies or favourable regulatory conditions.

Data privacy is central to IR5's human-centricity. The European Union's GDPR provides a global benchmark for digital ethics, emphasising consent, transparency, and individual rights.

Enforcement actions, such as fines levied against Meta, Amazon, Google, and H&M, illustrate the seriousness with which privacy is treated across the EU (European Data Protection Board, 2022). As IR5 systems rely increasingly on real-time data and AI, firms must incorporate data minimisation, algorithmic fairness, and transparent consent mechanisms into their system design. Ethical data practices are not only a compliance issue but a foundation for public trust in IR5.

Beyond regulation, market forces also drive digitalisation aligned with IR5. Karmaker et al. (2023) and Scuotto et al. (2023) find that firms operating in economies with high demand for personalised and sustainable offerings are more likely to adopt enabling technologies. However, external barriers persist, especially for complex implementations like blockchain in circular manufacturing. Kannan et al. (2024) identify key obstacles, including regulatory ambiguity, lack of stakeholder coordination, and infrastructure gaps that slow IR5-aligned innovation.

Together, these findings underline that IR5 implementation depends on an ecosystem of institutional support, regulatory clarity, and societal pressure, not just firm-level initiatives.

5.1.6 Societal expectations and ethical considerations

Rising societal expectations have placed new ethical demands on firms, particularly in relation to fairness, data stewardship, and social responsibility. Stakeholders increasingly expect companies to uphold fair labour standards, promote equitable access to technology, and contribute to the wellbeing of local communities.

Sharma et al. (2022) highlight that pharmaceutical manufacturers in Germany began transitioning toward IR5 not merely for operational efficiency but in response to cultural expectations for eco-friendly products and stringent data privacy. Similarly, Ejaz (2023) argues that societal pressure is pushing manufacturers to adopt sustainability-oriented strategies and reframe their digital transformation initiatives accordingly.

Public concern has also intensified around the ethical use of AI and data. Core issues include transparency, fairness, and accountability in AI-driven systems. Carayannis et al. (2023) propose that human-centric business strategies should be pursued precisely because of growing societal scrutiny. Without proper safeguards, the deployment of AI in production and management can result in privacy violations and discriminatory outcomes (Gagnidze, 2023; Pistolesi et al., 2024). These risks threaten not only individual rights but also the broader legitimacy of IR5 as a people-centred industrial paradigm.

Ultimately, societal expectations serve as both a constraint and a catalyst, shaping the ethical contours within which IR5 technologies are developed, deployed, and governed. Meeting these expectations is essential to realising IR5's vision of a socially inclusive and ethically grounded future. The key contextual factors that potentially affect IR5 progress are summarised in Table 5.

(Insert Table 5 here)

5.2 Processes of digitalisation toward IR5 goals

We identify three main digitalisation processes aligned with IR5's strategic objectives: enhancing human wellbeing, advancing sustainability, and fostering resilience. These processes reflect firm-level prioritisation, whereby specific technologies may support one or more goals depending on organisational capabilities and contextual constraints. Rather than attempting to achieve all goals simultaneously, firms may adopt phased strategies tailored to their maturity levels and strategic focus. For instance, Corallo et al. (2024) demonstrate how digitalisation in agri-food supply chains supports both circular economy principles and social inclusion, highlighting how sustainability and human-centricity can be jointly pursued through sector-specific innovation.

5.2.1 Resilience Driven Digitalisation

We identify three key digitalisation processes that enable firms to build resilience in the context of IR5: enhancing decision-making, fostering agile operations, and strengthening security and risk management.

First, digital tools such as real-time analytics, business intelligence (BI) systems, and AI-driven decision support platforms are crucial for improving forecasting and response capabilities. For example, Ordieres-Meré et al. (2023) found that data integration for handling structured and unstructured data supports early diagnosis and optimisation in production. Similarly, BI systems enhance resilience by enabling real-time monitoring and secure data storage (Sharma et al., 2022; Wang et al., 2023). Sharma et al. (2022) also demonstrate how AI enables pharmaceutical firms to customise medical solutions, reducing waste and ensuring responsiveness.

Second, agile processes, including rapid prototyping, iterative development, and cross-functional collaboration, help firms adapt quickly to change (Lu et al., 2022; Maddikunta et al., 2022). These approaches, which underpin mass customisation and human-centric production, are vital to IR5. However, Weick & Quinn (1999) caution that technological agility must be matched by organisational readiness, including shared meaning and cultural alignment. Armenakis & Harris (2009) further stress the importance of trust, leadership, and communication to institutionalise adaptive capacity. Thus, digital agility must be accompanied by cultural adaptability to ensure meaningful transformation.

Third, digitalisation supports robust security and risk management through advanced cybersecurity, scenario planning, and disaster recovery systems. Protocols such as encryption, audits, and cyber hygiene training ensure data and system integrity (Kumar & Mallipeddi, 2022; Rani & Srivastava, 2024). Peruzzini et al. (2023) show that resilience is also enhanced through human-machine collaboration, which improves performance, ergonomics, and safety in manufacturing. These integrated efforts not only protect systems but also reinforce workforce wellbeing and operational continuity.

Collectively, these practices demonstrate how digitalisation can systematically embed resilience into IR5 business strategies, provided they are aligned with organisational culture and supported by strong leadership and ethical governance.

5.2.2 Sustainability Driven Digitalisation

Digitalisation for sustainability in IR5 involves the adoption of smart operations, green manufacturing technologies, ethical AI practices, and inclusive design. These digitalisation processes enable firms to reduce waste, conserve energy, enhance transparency, and design systems that cater to diverse populations, all of which are key to achieving environmental and societal sustainability.

Smart operations are facilitated by technologies such as IoT, edge computing, cobots, digital twins, AI, and ML. AI and ML improve maintenance prediction and operational optimisation (Ahmed et al., 2023; El-Brawany et al., 2023; Hussain et al., 2023; Liao et al., 2023). IoT enables real-time machine monitoring, while edge computing enhances speed and reliability by processing data locally (Yao et al., 2022). These technologies reduce human error and operational inefficiencies. Digital twins further support design accuracy and operational optimisation by simulating and analysing real-world processes (Cutrona et al., 2023; Ejaz, 2023; Ivanov, 2023), which collectively lead to enhanced quality and waste reduction.

Green manufacturing, enabled by digital technologies, focuses on reducing the environmental impact of production. This includes using renewable energy sources, energy-efficient machinery, and sustainable materials (Yin & Yu, 2022). Caiazzo et al. (2023) propose an IoT-based green manufacturing framework comprising physical, cyber, monitoring, and smart decision-making layers to promote sustainable production.

While AI and additive manufacturing offer sustainability gains through precision and reduced material waste (Qahtan et al., 2022; Sharma et al., 2022), they also introduce environmental trade-offs. Deep learning systems are energy-intensive, increasing carbon emissions via data centres (De Vries, 2023). Additive manufacturing may consume significant energy depending on material and equipment types (Faludi et al., 2017). These trade-offs necessitate a critical evaluation of lifecycle impacts and systemic externalities. Destouet et al. (2023) emphasise using advanced analytics and IoT to monitor and optimise energy and water usage to minimise environmental footprints.

Ethical and inclusive design practices are equally vital for societal sustainability. Firms are urged to implement governance mechanisms for responsible AI use, addressing bias, transparency, and accountability, and ensure that digital systems are accessible to diverse user groups, including individuals with disabilities (Aydin et al., 2023; Battini et al., 2022; Cutrona et al., 2023). Without such frameworks, digital transformation may reinforce exclusion or deepen existing inequalities. Controversies over AI infrastructure, such as lawsuits related to water and land use, further highlight the need for public oversight and ethical governance (Crawford, 2021).

In sum, digitalisation for sustainability requires balancing technological benefits with ethical, social, and environmental responsibility. The following section explores how these practices relate to human wellbeing within IR5.

5.2.3 Human wellbeing driven digitalisation

IR5 places humans at the core, and all approaches, strategies, and processes should be designed to accommodate human needs. We found that *human-centric design and collaboration, personalisation*, and *skills development* are key processes by which firms can make progress in enhancing human wellbeing while conducting digitalisation.

Human-centric design and collaboration align with IR5's core principle of prioritising human value. Intelligent collaboration between human operators and thoughtfully designed machines enhances workplace efficiency and wellbeing (Caggiano et al., 2023; Grybauskas & Cárdenas-Rubio, 2024). Effective oversight of workforce-machine interaction throughout all stages of the firm lifecycle supports the creation of harmonised human-machine systems and shifts innovation toward a more human-centric focus (Carayannis et al., 2023; Carayannis et al., 2021).

Personalisation and configurability are also central to IR5. Rather than full-scale engineering customisation, firms increasingly adopt flexible systems that adapt to user-specific needs (Flanding et al., 2018). Technologies such as 3D printing and advanced CNC machining enable small-batch personalised production, while data analytics tools allow firms to interpret user preferences and adjust system settings accordingly (Jiménez-Partearroyo et al., 2023). For example, Human Asset Administration Shells and Human Digital Twins simulate operator behaviour to fine-tune production systems, enabling more tailored and responsive workplace environments (Cutrona et al., 2023).

Finally, skills development is essential to support human wellbeing and organisational adaptability. IR5 calls for continuous upskilling and reskilling to prepare employees for new roles focused on creativity, complex problem-solving, and ethical oversight. Investing in workforce development not only addresses potential talent shortages but also fosters inclusion and adaptability. Training in digital literacy, data analytics, and human-machine collaboration enhances performance and resilience (Panagou et al., 2023). Reskilling and upskilling programs enable firms to address the potential shortage of workforce required for IR5. Digital transformation not only demands technical skills but also shifts the nature of work, requiring new approaches to talent development and leadership (Montero Guerra & Danvila-Del Valle, 2024).

Collectively, these processes ensure that IR5's technological advancements serve to elevate human experience, not merely augment operational performance. Table 6 summarises the processes for achieving IR5 goals. We summarise the processes for achieving IR5 goals in Table 6.

(Insert Table 6 here)

5.3 Consequences

IR5 promises wide-ranging consequences that extend across organisational, economic, societal, and environmental domains. Unlike earlier industrial revolutions focused primarily on efficiency and automation, IR5 integrates values such as human wellbeing, sustainability, and resilience into the core of technological and strategic transformation. As Mouazen et al. (2025) argue, IR5 must be evaluated through the lens of Triple bottom-line sustainability, balancing economic value creation, social inclusion, and ecological stewardship. Their conceptual integration of Industry 5.0 with Society 5.0 and Digitised Value Chain 5.0 reinforces the notion of Innovation 5.0 as a holistic paradigm shift that redefines how value is produced, distributed, and experienced. This section explores the positive and negative consequences of IR5 across four key domains: firms, the economy, society, and the environment.

5.3.1 Potential impacts on firms

Integrating human-centric and sustainable practices with cutting-edge technologies can transform business operations, strategies, and models. We categorise three main potential impacts of IR5 on firms, including *operation efficiency and productivity, improved competitiveness,* and *business models*.

Operational efficiency and productivity are enhanced through automation, human-robot collaboration, real-time data analytics, and improved employee satisfaction. Cobots assist with repetitive or laborious tasks, freeing human workers for creative, strategic roles. Ordieres-Meré et al. (2023) report that implementing advanced IT systems reduced loading time by 35%, operator travel distance by 35%, and crane movement by 40% in a car manufacturer's logistics process, demonstrating measurable efficiency gains. Real-time analytics systems further improve decision-making and enable predictive maintenance and optimised resource allocation. Data from wearable devices, for instance, can be used to refine worker behaviour, leading to improved productivity and cost savings.

However, these data-driven practices raise serious privacy and ethical concerns. Continuous employee monitoring can verge on surveillance, especially when consent is ambiguous or uninformed (Zuboff, 2023). Wearables that track biometric and behavioural data risk exposing workers to profiling, breaches, and intrusive oversight (Moore, 2017). These issues necessitate strong data governance frameworks, transparent consent protocols, and ethical oversight to ensure technology serves human-centric purposes.

By automating routine tasks and fostering inclusive, innovation-oriented environments, firms can also enhance employee satisfaction and retention. Engaged workers are more productive, especially when involved in meaningful, creative work (Pasparakis et al., 2023). Agrawal et al. (2023) note that human-machine collaboration can reduce dependency on low-skill labour by optimising processes, improving quality, and enhancing operational efficiency.

IR5 also improves firm competitiveness through heightened responsiveness, production precision, transparent supply chains, and proactive customer engagement. Digital automation minimises human error and supports operational continuity (Ordieres-Meré et al., 2023). Peruzzini et al. (2023) found that Italian manufacturers leveraging digital tools were better able to comply with regulations, mitigate risks, and adapt to disruptions, thus reinforcing resilience and competitiveness. The synergy between AI, ML, and human creativity enhances innovation capacity, enabling rapid development of tailored products and services (Carayannis et al., 2023; Carayannis et al., 2021). Smart factories and real-time monitoring systems help lower costs while improving productivity and product quality. Digital tools also allow firms to deliver personalised customer experiences that boost satisfaction and loyalty (Roy et al., 2023; Sharma et al., 2022). In healthcare, for example, IR5 technologies support customised treatments, improving service quality and patient outcomes (Nayeri et al., 2023; Pistolesi et al., 2024).

Business models are evolving in tandem with IR5. Firms are shifting towards service-oriented approaches, including subscription models and pay-per-use schemes. Hussain et al. (2023)

found that the Indian hospitality sector has adapted its models to incorporate personalisation and human-machine collaboration, reflecting broader IR5 principles.

However, challenges remain. Increasing reliance on AI and predictive analytics may reduce transparency and amplify algorithmic bias, particularly if training data reflect historical inequities (Lu et al., 2022). Additionally, IR5's technical demands may worsen workforce stratification, privilege digitally skilled employees while sidelining others. These risks highlight the importance of inclusive digital transitions that prioritise equity, ethics, and organisational learning.

5.3.2 Potential impacts on the economy

The application of advanced technologies and the emphasis on personalised, ethical, and sustainable practices in the IR5 process will probably reshape industries and economic structures. We identify several aspects that IR5 can influence the economy, such as *economic resilience and growth, a green economy, global trade and economic interconnectivity,* and *global standards*.

The integration of IR5 technologies enhances economic resilience by enabling firms to absorb and recover from disruptions. When widely adopted, these capabilities aggregate into broader economic resilience. For example, technologies like AI, digital twins, and real-time analytics improve forecasting, mitigate supply chain vulnerabilities, and sustain operational continuity (Ivanov, 2022; Zhao et al., 2023).

IR5 also contributes to economic growth through efficiency improvements and new business models. Digital innovation, such as AI-enabled automation and virtual reality-assisted remote operations, enhances productivity and lowers costs (Lu et al., 2022). In the aerospace sector, for instance, the integration of AI, robotics, and IoT has increased operational efficiency, creating positive macroeconomic spillovers (Pérez et al., 2020).

Sustainability imperatives within IR5 further drive the emergence of green economic sectors. Technologies such as smart monitoring systems, renewable energy integration, and energy-efficient manufacturing platforms support eco-innovation and circular practices (Caiazzo et al., 2023). These developments encourage investment in low-carbon technologies and environmentally responsible business models, laying the foundation for a green economy.

In terms of globalisation, IR5 technologies facilitate enhanced trade flows and economic interconnectivity. Digital tools help firms streamline logistics, reduce lead times, and improve visibility across supply chains, thus enabling agile cross-border operations (Peruzzini et al., 2023; Sindhwani et al., 2022).

However, these advancements also create a growing need for global interoperability standards. As firms adopt technologies under IR5 imperatives, governments and international organisations must collaborate to harmonise standards for data sharing, cybersecurity, and ethical technology governance (Agrawal et al., 2023).

Nevertheless, the economic benefits of IR5 may be unequally distributed. Small and medium-sized enterprises (SMEs), especially in the Global South, may lack the digital infrastructure, institutional support, or skilled workforce needed to fully benefit from IR5 transformation. This digital divide could widen existing global disparities unless addressed through inclusive policy frameworks and international cooperation (Jackson, 2016; Kallis et al., 2020).

5.3.3 Potential impacts on society

With its focus on human-machine collaboration, IR5 is anticipated to make profound impacts on society through *enhanced quality of life*, *social inclusivity and equality*, *job transformation,* and *workforce development*.

Enhanced quality of life is a central promise of IR5. Improved work conditions, worker health, and personalised services contribute directly to wellbeing. Integrating cobots and exoskeletons alleviates physical strain and repetitive tasks, creating safer, more ergonomic, and fulfilling work environments (Grosse, 2024; Peruzzini et al., 2023). Human-machine collaboration supports worker welfare, privacy, and rights (Choi et al., 2022) while also addressing health concerns such as air pollution (Qahtan et al., 2022), promoting diversity and inclusion (Cillo et al., 2022), reducing gender inequality (Aydin et al., 2023), and enhancing job satisfaction and self-efficacy (Helm et al., 2023; Pasparakis et al., 2023). In healthcare, IR5 technologies like AI-driven prognostics and wearable health monitors can improve outcomes and access to care (El-Brawany et al., 2023; Nayeri et al., 2023; Pistolesi et al., 2024).

Social inclusivity and equality are also advanced through accessible technologies and digital empowerment. IR5 calls for inclusive designs that cater to diverse populations, including people with disabilities. Examples include advanced work instructions to support disabled workers (Peltokorpi et al., 2023) and human-centric communication systems for workers with varying abilities (Panagou et al., 2023). Providing digital literacy training and democratising access to technology helps bridge the digital divide and empower marginalised groups with new opportunities in education, employment, and economic participation (Cillo et al., 2022).

IR5 also drives job transformation and workforce development. Digital tools and flexible work arrangements support remote work and decentralised labour markets (Lu et al., 2022), which can rejuvenate rural areas and improve work-life balance. While automation may replace some routine jobs (Liao et al., 2023), IR5 creates new roles requiring creativity, problem-solving, and technological proficiency (Cutrona et al., 2023). The role of warehouse managers, for instance, has evolved toward strategic workforce oversight (Grosse, 2024). A continuous learning culture and upskilling initiatives are vital for ensuring employees remain adaptable and relevant in an IR5-enabled environment (Dornelles et al., 2023; Hussain et al., 2023).

However, the societal promise of IR5 is not without risks. Increased use of wearables and AI raises concerns about digital surveillance, privacy, and autonomy. Continuous data collection can blur the line between performance monitoring and intrusive oversight, especially when consent is vague or inadequately obtained (Zuboff, 2023). Ethical design and strong data governance are crucial to protecting individual rights.

Moreover, the integration of AI into decision-making introduces risks such as job displacement, de-skilling, and algorithmic bias, particularly when AI systems are trained on non-representative data (Lu et al., 2022). Legal and social resistance to data centre infrastructure further underlines the need for inclusive governance and sustainable design (Crawford, 2021).

Thus, while IR5 promises societal benefits such as inclusivity and wellbeing, these depend on the ethical implementation, cultural sensitivity, and governance of digital technologies within diverse social contexts.

5.3.4 Potential impacts on the environment

Given IR5's focus on sustainable technological advancement, it has the potential to be less environmentally damaging than previous industrial revolutions by promoting resource sustainability, minimising environmental footprints, and enhancing climate resilience.

Integrating IR5 technologies helps sustain natural resources through activities such as resource optimisation, ecosystem simulation using digital twins, and waste reduction. Deploying advanced analytics, smart sensors, and IoT systems enables real-time tracking of resource use, improving efficiency and reducing waste of water, raw materials, and energy (Agrawal et al., 2023; Psarommatis et al., 2023). Using digital twins to simulate and manage ecosystems can mitigate industrial impacts on the environment. Barata & Kayser (2024) note that digital twins are fundamental to IR5, enabling virtual design and optimisation without physical expansion. Additive manufacturing and precision engineering also promote efficient material use and lower emissions (Qahtan et al., 2022; Sharma et al., 2022). For instance, Agrawal et al. (2025) show how IR5 principles contribute to circular pharmaceutical supply chains and reduce waste.

IR5 also enables practices that reduce environmental footprints. Eco-friendly product design, sustainable manufacturing technologies, and circular economy models (e.g., reusing and recycling materials) are essential. Yuan et al. (2022) highlight how IR5 fosters product designs that minimise environmental impact. Caiazzo et al. (2023) present an IoT-based smart monitoring system that enhances sustainable production and workplace safety. Automation and intelligent monitoring can help manage pollution control systems, reducing emissions into air, water, and soil (Qahtan et al., 2022).

IR5 encourages infrastructure that is resilient to climate change and extreme weather, ensuring continuity and adaptability. Human-machine collaboration in IR5 also supports environmental conservation and climate change mitigation (Agrawal et al., 2023; Psarommatis et al., 2023). Gagnidze (2023) suggests that IR5 progress may stimulate new environmental protection laws.

Nevertheless, technologies like AI and additive manufacturing also pose environmental challenges. AI, particularly deep learning, demands substantial computational power, generating high carbon emissions (De Vries, 2023). Additive manufacturing, while reducing waste, can be energy-intensive (Faludi et al., 2017). Data centre expansion has also triggered legal disputes over water use and land rights (Crawford, 2021).

In summary, while IR5 technologies offer promising environmental benefits, they also entail trade-offs. Claims of sustainability must be critically assessed through lifecycle analysis and independent oversight. A balanced understanding of IR5 requires acknowledging that its innovations can produce both gains and risks. For example, wearables can enhance productivity but raise privacy concerns; additive manufacturing can reduce waste but increase energy demand. Table 7 summarises these trade-offs across four domains: firms, the economy, society, and the environment.

(Insert Table 7 here)

6 DISCUSSION

6.1 Integrative framework

Based on our analytical findings, we propose an integrative framework, referred to as the IR5 CPC model, that captures the contextual conditions (C), transformation processes (P), and resulting consequences (C) of Industry 5.0 (IR5). Figure 1 illustrates this framework.

(Insert Figure 1 here)

The first component, contextual conditions, encompasses organisational enablers (visionary leadership, dynamic, agile and inclusive culture, and technological readiness) and environmental factors (digital literacy, supportive economic and regulatory frameworks, and societal expectations for ethical conduct). These conditions can either enable or constrain IR5 adoption depending on the surrounding internal and external dynamics. As such, firms must assess not only their strategic goals but also readiness gaps and institutional pressures. We propose:

> ***Proposition 1****: To implement digitalisation aligned with IR5 goals, firms need six key contextual conditions: visionary and transformational leadership, dynamic, agile and inclusive organisational culture, technological readiness, a digitally literate workforce, supportive economic and regulatory frameworks, and strong societal expectations for ethical and sustainable outcomes.*

The second component, processes, highlights three key digitalisation trajectories aligned with IR5's guiding goals: resilience, sustainability, and human wellbeing. These include (i) data-driven decision-making, agile systems, and risk management; (ii) smart operations, green manufacturing, and ethical design; and (iii) human-centric design, personalisation, and continuous workforce development. While these goals are interrelated, firms often lack the capacity to address them all simultaneously. Accordingly, we posit:

> **Proposition 2:** *A phased and adaptive digitalisation strategy is more feasible for achieving IR5 goals. Firms are likely to adopt resilience-enabling technologies first, then progressively target sustainability and human-centric outcomes, balancing resource constraints and managing socio-technical risks.*

The third component, consequences, reflects the dual outcomes of IR5 across four impact domains: firms, the economy, society, and the environment. This model acknowledges both positive effects, e.g., operational efficiency, economic resilience, inclusivity, and resource optimisation, and associated risks, e.g., job displacement, algorithmic opacity, digital divides, and ecological burdens. We therefore propose:

Proposition 3: *Digitalisation toward IR5 goals will yield both benefits and risks, including (i) improved firm-level efficiency, competitiveness, and innovation, alongside threats like job stratification and surveillance; (ii) economic growth, green innovation, and global trade expansion, tempered by unequal access and SME marginalisation;(iii) improved societal wellbeing and workforce development, offset by privacy and autonomy concerns; (iv) environmental gains in resource efficiency and resilience, constrained by energy use, material dependency, and unresolved externalities.*

Figure 1 reflects this balanced model, showing how contextual enablers and constraints influence digital transformation pathways and generate mixed consequences across domains.

This integrative framework contributes to the literature on change management by illustrating how firms can engage in context-sensitive, goal-aligned digital transformation. It supports adaptive strategies, stakeholder governance, and iterative learning, which are principles echoed in foundational change management theory (Armenakis & Harris, 2009).

6.2 Theoretical Contributions

This paper makes three distinct theoretical contributions to the literature on Industry 5.0, and organisational change. ***First***, we provide a foundational reconceptualization of IR5 by defining it as a socially constructed framework that reconfigures industrial systems through the integration of human-centricity, sustainability, and resilience into advanced digitalisation. This definition extends the European Commission's (2021b) policy framing by theorising IR5 as a normative and strategic shift from the automation- and efficiency-driven logics of Industry 4.0. While IR4 prioritised technological optimisation, IR5 repositions digitalisation as a vehicle for achieving more inclusive, ethical, and context-sensitive outcomes. Our definition synthesises emerging IR5 literature and establishes clear conceptual boundaries that distinguish IR5 from

IR4, offering a robust theoretical foundation for future research on organisational transformation in the digital age.

Second, we develop the IR5 CPC (Conditions-Processes-Consequences) framework, an integrative, multi-level model that captures the organisational and institutional dynamics of IR5-driven transformation. This framework contributes to change management theory by linking contextual enablers (e.g., visionary leadership, digital readiness, stakeholder expectations) with digitalisation processes aligned to IR5 goals (human well-being, sustainability, and resilience), and mapping their dual consequences, both benefits and risks, across firms, societies, and ecosystems. Unlike prior literature that remains sector-specific or techno-centric (e.g., Coronado et al., 2022; Agrawal et al., 2023), our model adopts a socio-technical lens that connects enabling conditions with broader system-level trade-offs. For example, Agrawal et al. (2023) focus narrowly on supply chain resilience; Coronado et al. (2022) address HRI in manufacturing; Enang et al. (2023) examine IR4-IR5 transitions without exploring outcomes; Ghobakhloo et al. (2023a; 2023b) propose roadmaps and definitions but do not integrate institutional variation or system-wide impacts. Others (e.g., Grabowska et al., 2022; Leng et al., 2022; Psarommatis et al., 2023; Tlili et al., 2023) focus on individual components but fail to offer an overarching synthesis. Even recent reviews such as Sneha and Kavitha (2024), Panigrahi et al. (2025), and Ali et al. (2025) illustrate this fragmentation by addressing specific domains (creative economy, inventory knowledge, regional synthesis) without cohesive theorisation across levels. In contrast, our CPC framework offers an interdisciplinary and systemically connected model that unifies these fragmented insights into a coherent understanding of IR5 transformation.

Third, we contribute to theoretical integration by embedding IR5 research within established frameworks in organisational change and innovation studies. Specifically, we draw on Socio-technical Systems Theory, the Capability Approach, Innovation Diffusion Theory, and Complexity Theory to explain how firms adapt to IR5 under uncertainty, institutional multiplicity, and competing stakeholder demands. These perspectives offer critical explanatory tools for understanding resistance, ethical governance, and adaptive capacity, issues often overlooked in the largely techno-optimistic IR5 discourse. By engaging with these theoretical traditions, our model positions IR5 transformation within broader conversations about inclusive, context-sensitive, and ethically attuned organisational change.

In sum, this paper advances theoretical understanding of Industry 5.0 by offering a refined conceptualisation, an integrative CPC framework, and a roadmap for theoretical integration—contributing to both scholarly inquiry and change-oriented practice.

6.3 The current stage of existing literature and future research suggestions

Our analytical review reveals that while the concept of IR5 has gained momentum since 2021, the literature remains fragmented and predominantly conceptual. Contributions span management subfields, such as information systems, operations, innovation, and organisational behaviour, as well as adjacent domains like sociology and economics. Much of this work focuses on thematic silos, including human-robot interaction, green manufacturing, or policy perspectives, without integrating the full spectrum of IR5's socio-technical dimensions. Drawing on our CPC (Conditions-Processes-Consequences) framework, we identify substantial gaps in empirical analysis, particularly concerning how IR5-aligned processes are operationalised within organisations. Figure 2 details the research stage of each model element, summarising key findings with * (conceptual studies) and ** (empirical studies). Future research should investigate topics marked with * that lack empirical evidence.

(Insert Figure 2 here)

One promising but under-theorised area involves the use of standard operating procedures (SOPs) in guiding digital transitions. In practice, multinational firms are increasingly formalising IR5-aligned routines through AI- and enterprise resource planning (ERP)-based SOPs. For example, Nestlé's phased SAP ERP[2] rollout integrates predictive analytics and machine learning into supply chain operations. Similar practices have emerged at Siemens[3], GE[4], Boeing, and NASA, where SOPs encode AI and cyber-physical systems into routine workflows. Despite their strategic relevance, such tools have received little scholarly attention. Future research should investigate how SOPs function as mechanisms of organisational change, shaping routines, capability development, and digital transformation pathways under IR5.

In addition to empirical gaps, theoretical integration remains limited. Many existing studies either adopt no theoretical lens or rely on single-theory applications, which insufficiently capture the complexity of IR5 transformations. We advocate for a multi-theoretical approach that synthesises complementary perspectives. Socio-technical Systems Theory (Emery & Trist, 1960) can illuminate the interaction between social systems and technical infrastructure, particularly in understanding how human-centric technologies reshape work environments. Social Representation Theory (Moscovici, 1984) helps explain how societal norms and collective imaginaries influence the reception and meaning of IR5 innovations.

To better understand technology adoption and interaction, we recommend combining Innovation Diffusion Theory (Rogers, 2003) and Human-Computer Interaction (Card et al., 1983), which can elucidate how AI, cobots, and digital tools are introduced, accepted, and adapted within organisations. The Capability Approach (Sen, 1999) offers a human

[2] https://www.sap.com/uk/about/customer-stories/nestle.html
[3] https://press.siemens.com/global/en/pressrelease/siemens-introduces-ai-agents-industrial-automation
[4] https://www.geaerospace.com/news/press-releases/ge-aerospace-boeing-and-nasa-study-performance-installed-open-fan-engine-design

development perspective, focusing on how IR5 technologies can expand individual agency, dignity, and workplace wellbeing. Lastly, Complexity Theory (Mitchell, 2009) provides a systems-level lens for exploring the adaptive, emergent, and often unpredictable dynamics of IR5 implementation across interconnected organisational and societal layers.

To advance theoretical understanding in IR5 research, future studies should move beyond isolated or juxtaposed theories. We advocate a synthesis approach where intersecting lenses, such as Complexity Theory and Socio-technical Systems Theory, are used to construct more nuanced, integrated accounts of IR5 change processes. By embedding these theoretical perspectives into empirical research, scholars can better capture the multifaceted, adaptive, and contested nature of digital transformation in the Fifth Industrial Revolution.

6.4 Practical Implications

6.4.1 Implications for change management practice

Building on our IR5 CPC model, this subsection outlines key insights for practitioners leading change within organisations. Industry 5.0 introduces a more complex digital transformation agenda, which demands more than technology adoption; it calls for human-centred adaptation, inclusive governance, and values-driven redesign of core systems. Our findings suggest that managing IR5 change effectively requires a phased, flexible approach that aligns with organisational realities.

First, organisations must begin by assessing readiness across multiple dimensions. This means evaluating the maturity of digital infrastructure, the skills and attitudes of employees, and the adaptability of the organisational culture. As the role of formal human resources development practices evolves, companies must prioritise work-embedded digital tools that stimulate informal learning and agility in employee development (Piwowar-Sulej et al., 2024).

Understanding these baselines helps change leaders tailor strategies that are both realistic and impactful.

Second, digital transformation under IR5 should not be linear. Instead, leaders should sequence change initiatives by aligning them with firm-specific needs, starting with resilience to stabilise core operations and gradually extending to sustainability and human-centric design. A modular roadmap supports prioritisation and risk management in complex environments.

Third, SOPs (Standard Operating Procedures) can serve as powerful enablers of routinised change. As seen in organisations like Siemens and Nestlé, SOPs provide a means to institutionalise best practices, embed ethical safeguards, and facilitate consistency across geographically distributed teams. However, SOPs must be co-designed with those affected to ensure usability and legitimacy.

Lastly, ethical and human issues must be foregrounded, not addressed retrospectively. As AI, ERP, and other digital systems expand, change leaders need to safeguard data privacy, worker wellbeing, and inclusion. This means embedding ethical design principles from the outset and engaging stakeholders in ongoing dialogue about the impacts and direction of transformation.

Together, these strategies equip change managers with tools and perspectives to navigate IR5's contested, multi-stakeholder terrain with clarity and responsibility.

6.4.2 Policy and strategic implications

While Section 6.4.1 offers guidance for change managers within organisations, this section extends the implications of IR5 to broader strategic and policy domains. Business leaders must translate IR5 principles into strategic advantage by embedding human-centric, sustainable, and resilient practices into core operations, not as isolated initiatives but as integral parts of digital strategy. At the same time, policymakers must foster enabling ecosystems that ensure equitable and responsible IR5 transitions across industries and regions.

For Business Leaders: Organisations that delay engagement with IR5 risk falling behind competitors that are already reconfiguring their operations around resilience, human-centricity, and sustainability. However, transitioning to IR5 is not a one-size-fits-all process. Leaders should articulate a staged digitalisation roadmap that aligns with firm-specific capabilities and priorities. Our framework supports this approach by detailing processual pathways that enable firms to either phase IR5 goals sequentially or integrate them in tandem where feasible.

Importantly, leaders must also consider the ethical, environmental, and human consequences of digitalisation. SOPs for AI, ERP systems, and other cyber-physical integrations must reflect not only performance metrics but also safeguards for data privacy, inclusion, and sustainability. For example, global firms such as Nestlé and Siemens are already embedding AI-enhanced ERP routines into their operations using standardised, human-centred procedures, highlighting that IR5 alignment requires organisational design innovations, not just technology upgrades.

For Policymakers and Institutional Stakeholders: Policy must evolve in tandem with firm-level transformation. Regulatory frameworks should promote responsible digital adoption while mitigating externalities such as carbon-intensive AI infrastructure, algorithmic bias, and digital labour exploitation. This includes enforcing data protection through GDPR-style measures and incentivising green and inclusive innovation through targeted subsidies or R&D grants.

Additionally, policymakers should act as change facilitators by supporting ecosystem-wide capacity building. This involves investing in digital skills training, funding applied research on IR5 implementation, and disseminating best practices through public-private partnerships.

Tailored support for SMEs and low-resource regions will also be essential to ensure IR5 does not widen existing digital or economic divides.

7 CONCLUSION

This study develops a comprehensive understanding of IR5 by critically analysing prior literature and proposing a conceptual framework that captures the enabling conditions, digitalisation processes, and systemic consequences of IR5 implementation. The framework provides a theoretical foundation for examining how organisations navigate IR5 transformations, identifying both drivers and barriers, as well as the implications for business operations and broader macro-level change.

Notably, the study demonstrates that the outcomes of IR5 are contingent upon how technologies are governed, embedded in organisational routines, and ethically aligned with institutional values. Recognising the dual nature of IR5 (potential benefits and risks) is essential for fostering socially responsible and environmentally sustainable innovation strategies. In addition to synthesising fragmented scholarship, this paper identifies key gaps in empirical research and offers practical guidance for policymakers, business leaders, and organisational change practitioners.

Despite its contributions, the study has several limitations. *First*, as a conceptual analysis based primarily on academic literature and policy reports from major international organisations, this study may overlook valuable insights from practitioner-oriented publications and industry sources. *Second,* the manual content analysis may introduce subjectivity, although this was mitigated through multiple rounds of author triangulation. *Third,* while empirical findings were organised thematically to align with our research aims, alternative categorisation approaches remain unexplored and warrant future consideration.

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TABLE 1 Summary of Industry 5.0 definitions offered by prior literature

Sources	Industry 5.0 Definition	Comments
Agrawal et al. (2023)	Industry 5.0 is a revolution process that aims to make industries more compatible, sustainable, human critical thinking-centric, and resilient by enhancing technologies to overcome disruptions in the supply chain process.	Not cover sustainability
Asif et al. (2023)	Industry 5.0 resets economic and social balance responsibly, focusing on enhancing sustainability and transitioning towards a digital society, and combining human-centred workplaces with advanced technologies for societal benefits.	Not cover resilience
Enang et al. (2023)	Industry 5.0 is a value-centric paradigm that builds upon the principles of Industry 4.0, aiming to balance economic development with the resolution of societal and environmental problems. It represents a shift from a focus on shareholder value to stakeholder value, considering the well-being of industry workers and respecting environmental limits to growth.	Not cover resilience
Ivanov (2023)	Industry 5.0 is a multifaced phenomenon that draws on technological innovations, organisational principles, and managerial practices to promote sustainability.	Not cover resilience and human-centric
Ghobakhloo et al. (2023a)	Industry 5.0 is a concept that represents the vision of a sustainable future industry, going beyond traditional productivity and consumption-driven economic models. It aims to address economic and socio-environmental issues such as regional development, income polarization, labour market disruption, and environmental degradation. Industry 5.0 emphasizes sustainability as the core objective of digital industrial transformation, complementing the features of Industry 4.0.	Not cover resilience
Psarommatis et al. (2023)	Industry 5.0 is a concept that emphasizes the integration of human-centred and AI-driven strategies, focuses on the collaboration between humans and machines, where humans play a crucial role in decision-making and problem-solving, while machines provide support through automation and advanced technologies, for achieving efficient and sustainable manufacturing systems.	Not cover sustainability
Tlili et al. (2023)	Industry 5.0 refers to the next phase of industrial development that focuses on integrating human-centricity, sustainability, and resilience into manufacturing processes within the metaverse, which aims to combine the strengths of humans and machines, emphasizing the importance of human involvement in the production chain.	Comprehensive
Coronado et al. (2022)	Industry 5.0 is a paradigm shift prioritizing human well-being while maintaining production performance, addressing social and planetary challenges neglected in previous industrial revolutions.	Not cover sustainability
Leng et al. (2022)	Industry 5.0 is a dynamic and evolving paradigm that pursues the vision of co-creative and shareholder-driven industrial development, aiming to achieve societal goals beyond jobs and economic growth, and further achieve sustainable development goal of a supersmart society and ecological values.	Not cover resilience and human-centric
Maddikunta et al. (2022)	Industry 5.0 is a human-centric design solution where the ideal human companion and cobots collaborate with human resources to enable personalisable autonomous manufacturing through enterprise social networks.	Not cover resilience and sustainability.
Carayannis et al. (2021)	Industry 5.0 is a human-centred industrial paradigm focusing on societal benefits that integrates innovation policy, entrepreneurial spirit, and skills for societal advancement.	Not cover resilience
Xu et al. (2021)	Industry 5.0 is an evolutionary paradigm that complements Industry 4.0 by driving innovation to promote environmental and social values.	Not cover resilience and human-centric

Source: Authors own work

TABLE 2 Summary of Industry 5.0 definitions offered by International Organisations

Sources	Industry 5.0 Definition	Comments
European Commission (2024)	Industry 5.0 is a transformative vision for industry that extends beyond economic growth to contribute to societal well-being and environmental sustainability by integrating human-centric values, resilience, and sustainability into industrial processes.	Comprehensive
European Commission Report (2021)	Industry 5.0 should be, unlike Industry 4.0, around three core values, namely human-centricity, sustainability, and resilience, calling industries to re-think their positions and roles in society. It recognizes the power of industry to achieve societal goals beyond jobs and growth to become a resilient provider of prosperity by making production respect the boundaries of our planet and placing the well-being of the industry worker at the centre of the production process.	Comprehensive
European Bank for Reconstruction and Development (EBRD) (2025)	This report discusses industrial policies, digital technologies, and their impact on services and manufacturing. It also discusses how digital technologies can enhance efficiency, reduce costs, and contribute to more agile and productive industries with an emphasis on human capital and sustainability, reflecting Industry 5.0 themes in the context of transition economies.	Comprehensive
UNIDO (2025)	While UNIDO doesn't provide a distinct "Industry 5.0" definition, their work promotes sustainable manufacturing practices, the adoption of green technologies, and the enhancement of human capital in industrial settings. These efforts directly contribute to the sustainability and human-centric goals of Industry 5.0. Their focus is on practical solutions for developing countries to achieve industrialization in a responsible and beneficial way.	Comprehensive
UNCTAD (2025)	Although UNCTAD (2025) does not provide a specific definition of IR5, its ‘Technology and Innovation Report 2025’ touches on many aspects relevant to Industry 5.0, such as leveraging AI for productivity and workers' empowerment, and global collaboration for inclusive and equitable AI. This strongly aligns with IR5 principles. As it is needed for technological advancements to be inclusive, sustainable, and contribute to human well-being and development. This aligns with the human-centric and sustainability aspects of Industry 5.0, particularly in the context of developing countries.	Comprehensive
World Bank (2025)	World Bank sees the elements of Industry 5.0 as crucial aspects of a successful and equitable digital transformation that contributes to their overarching mission of investing in upskilling or reskilling people, advising organizations proactively adapt to rapid transformations driven by automation, digitalization, and climate action and promoting digital and green transition.	Comprehensive
World Economic Forum (WEF) (2025)	The fifth industrial revolution, or Industry 5.0, is defined by the convergence of various technologies across major industrial sectors. This revolution envisions a future where intelligent machines possess cognitive abilities comparable to humans, while simultaneously maintaining machine-level efficiency. This technological convergence is anticipated	Comprehensive

	to bring significant advantages to people, the planet, and profitability. It emphasizes a collaborative ecosystem where technology supports and empowers human workers.

Source: Authors own work

TABLE 3 Key features of industrial revolutions

Dimension	Industry 1.0 (18th -19th Century)	Industry 2.0 (19th - 20th Century)	Industry 3.0 (Late 20th Century)	Industry 4.0 (Early 21st Century)	Industry 5.0 (21st Century)
Known as	Industrialization	Mass production	Automation	Digitalization	Human-tech partnership
Objectives	Efficiency and productivity	Efficiency and productivity	Efficiency and productivity	Efficiency and productivity	Human well-being Sustainability Resilience
Human role	Manual labour in factories	Specialized roles in mass production	Knowledge workers in digital industries	Collaborators with AI and automation	Co-creators with intelligent systems
Skill requirements	Basic manual and artisanal skills	Technical and specialized skills	Digital and analytical skills	Digital literacy, data science, programming	Creativity, complex problem-solving, ethical AI
Technology integration	Steam engines Mechanized textile technology	Electricity Chemical synthesis Steel production	Computer-based systems Semiconductors Internet	IoT AI Advanced robotics Addictive manufacturing	Human-machine synergy Cobots
Industrial sectors	Coal and steam power for cotton mills and ironworks	Automobile industry	Computing industry	Digital sector	Smart manufacturing
Systemic approaches	Mechanized production	Assembly line/mass production	Automated production process	Real-time data monitoring production	Real-time data monitoring production to advance human value
Production focus	Mechanization	Electrification and mass production	Digital and automated manufacturing	Smart factories and cyber-physical systems	Mass personalization and sustainable production
Work environment	Factories and workshops	Assembly lines and industrial plants	Offices and digital workspaces	Hybrid and smart workspaces	Augmented and personalized work environments
Leadership style	Authoritative, top-down	Bureaucratic and hierarchical	Transformational and adaptive	Visionary, tech-savvy	Human-centric, inclusive, ethical leadership
Innovation drive	Mechanization and efficiency	Product standardization and scalability	IT and software development	AI-driven innovation and connectivity	Sustainable innovation, human-centric design
Customer interaction	Limited and indirect	Mass market and standardized products	Customized digital solutions	Connected and real-time customer engagement	Deep personalization and active participation
Workforce dynamics	Low-skilled labour, child labour	Skilled trades, growing middle class	Tech professionals, gig economy	Blended workforce with automation	Diverse, empowered, lifelong learners
Sustainability focus	Minimal	Emerging environmental awareness	Initial focus on green tech	Advanced sustainability and efficiency	Integral to operations and strategy
Risk and Resilience	Basic risk management	Industrial safety and quality control	Cybersecurity and data protection	Resilient, digitally secured supply chains	Ethical AI, robust risk management frameworks
Impact on: Economy, Society, Environment	Rise of the factory system Urbanization Resource extraction	Rise of corporations Consumer culture Increased pollution	Global supply chain Information age Greenhouse gas emission	Digital economy Data privacy issues Efforts towards resource efficiency	Smart economy Job satisfaction Efforts towards a green planet

Source: Authors own work

TABLE 4 Industry 5.0 technologies and definitions

Industry 5.0 Technologies	Definitions
Human-centric solutions	
Advanced extended reality	An enhanced version of reality created using technology to overlay digital information on an image of something being viewed through a device, it is a universal term inclusive to immersive learning technologies virtual reality (VR), augmented reality (AR), and mixed reality (MR).
Augmented reality (AR)	Technology for product visualization, marketing campaigns, architecture and home design, education, and industrial manufacturing.
Extended reality (ER)	Technology that merges both real and virtual environments, such as VR, AR, and mixed reality.
Intelligent personal assistant	Applications that utilise AI and data processing to assist in performing a wide range of tasks, e.g., information searches.
IoT and sensor technologies	Devices equipped with self-identification capabilities, localization, diagnosis status, data acquisition, processing, and implementation. They are connected through standard communication protocols.
Robotic process automation (RPA)	Technology to automate various supply chain processes, including data entry, predictive maintenance, and after-sales service support.
Virtual reality (VR)	Applications such as video games, 3D cinema, amusement park rides, and social virtual worlds.
Bio-inspired technologies	
Collaborative robots (cobots)	Robots that are equipped with sensors. They are designed to work in tandem with humans to enhance human efficiency, and the collaborative manner optimizes the capabilities of both cobots and humans.
Exoskeletons	Wearable devices are positioned between one or more joints on the human body and can perform physical work. Industrial exoskeletons are able-bodied devices designed to augment workers who are performing specific, repetitive physical tasks.
Wearable technology	Digital devices can be worn as accessories, embedded in clothing, implanted in the user's body, or even tattooed on the skin.
Wireless sensor networks	Digital systems that can respond to and detect some kind of input from both physical and environmental conditions.
Real-time digital twins	
5G	A cellular network that enables a ground-breaking advancement that facilitates comprehensive connectivity encompassing individuals, machines, objects, and devices.
6G	A cellular network that operates in untapped radio frequencies and uses cognitive technologies like AI to enable high-speed, low-latency communication at a pace multiple times faster than fifth-generation networks.
Digital twins	Technology that can digitally replicate a physical system or an object. It effortlessly integrates data between a physical machine and its digital counterpart in the virtual world, either in real time or through historical data.
Human digital twins	Technology that produces a digital replica of a real human in cyberspace.
Cyber-safe data transmission	
Blockchain	Technology that facilitates the secure exchange of information. The transactions are recorded in a record book, commonly referred to as a ledger. Blockchain provides a platform for the permanent, immutable, and transparent logging of data and transactions.
Cloud data and computing	Technology to enable ubiquitous, convenient, on-demand internet access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services).
Cyber-physical systems	A system that models, automates, and controls the mechanism of a physical system within a digital environment.
Cybersecurity technologies	Technologies to combat threats against networked systems and applications, including theft of sensitive data.
Artificial intelligence	
Advanced AI	aka augmented intelligence, technologies used for fostering synergies between human and computer intelligence.
Advanced generation IoT	Technology with embedded intelligence to perform a real-time analysis of information.
Cognitive computing	The application of computerized models to emulate human thinking processes in complex scenarios where the solutions may be ambiguous and uncertain.
Digital product lifecycle management	Applications are used in manufacturing to manage a product and its associated data through all stages of the product lifecycle.
Forecasting/predictive analytics	Applications are used for continuous adjustment of forecasts to identify new opportunities and risks early and grow profitably.
Technologies for energy efficiency and reliable autonomy	
Additive manufacturing	aka 3D printing, technologies for prototyping (to support the product development process, static simulation and wind tunnels, etc.), manufacturing, maintenance and repair, and modeling phases, e.g., drugs, dentistry, automotive sector, construction, customized tools.
Automatic guided vehicle (AGV)/Drones	Digital devices are used for manufacturing, warehousing, inspection, exploration, transportation, and military.
Automation and industrial robotics	Digital devices used to replace manual labour and increase efficiency, speed, and overall performance.
Autonomous vehicles	Technology that relies on sensors, actuators, complex algorithms, machine learning systems, and powerful processors to execute software.
Big data analytics	Applications for planning and forecasting, predictive maintenance and simulation in manufacturing, supply chain management and maintenance. The data can come from IoT systems connected to the productive layer (e.g., with sensors and associated equipment), or the exchange between IT systems for production and warehouse management.
Computer-aided manufacturing (CAM)	Application to enable manufacturers to create better parts with increasingly more control over the entire process.
Connected systems for intelligent manufacturing	Applications that leverage cloud computing to gather operational and business data to assist manufacturers in improving their processes.
Industrial control systems	Application to control industrial processes such as manufacturing, product handling, production, and distribution.
Machine learning	Technology is used in Internet search engines to handle large amounts of data and identify market trends and patterns.
Machine to Machine (M2M) technologies	Technology to capture and transmit data according to specific applications through multiple wireless technologies.
Manufacturing execution system	Application to manage and optimize production processes, raising outputs and increasing efficiency.
Proactive maintenance and data-driven prognostics	Applications for proactive maintenance, a maintenance strategy that aims to identify and rectify the causes of equipment failure before they occur.
Product identification (e.g., RFID, RTLS)	Application to enable the automatic identification and tracking of parts and products, allowing operational processes to become more transparent, efficient, and secure.
Smart manufacturing	Systems that employ computer-integrated manufacturing, high levels of adaptability, rapid design changes, digital information technology, and more flexible technical workforce training.
Smart materials	Materials to create more efficient and responsive sensors, actuators, and similar devices.

Source: Authors own work

TABLE 5 Contextual conditions and their impacts on Industry 5.0 implementation

	Contextual condition	Key aspects	Impact on implementation
Organisational factors	Visionary leadership	Shift of business mindset; guide and inspire team members; managerial and change management awareness.	Aligns with the goals of Industry 5.0 to support a culture of innovation, inclusivity, and adaptability and foster an environment where employees feel empowered to leverage technology for creative and strategic purposes.
	Dynamic organisational culture	Agile processes; open innovation to experimentation, learning, and adaptation.	Ensures organisations can innovate constantly, swiftly adopt and integrate new technologies, and allow flexibility and rapid adaptation to these changes.
	Technological readiness	Advanced tech; digital infrastructure and facilities; interoperability standards.	Enables seamless integration of Industry 5.0 technologies into operations in industries such as manufacturing, transportation, healthcare, etc., with substantial technological applications.
Environmental factors	Digital literate workforce	Skill development in data analytics; human-machine collaboration.	Prepares employees to effectively use and collaborate with advanced technologies to achieve economic impact.
	Economic and regulatory frameworks	Incentives and funding; regulatory compliance; strong market demand.	Steering firms' strategies, providing a supportive environment for investment and growth in Industry 5.0.
	Societal expectations and ethical consideration	Social responsibility; customer expectations; ethical AI use.	Aligns organisational practices with societal values and expectations and ensures transparency, fairness, and accountability in using AI technologies.

Source: Authors own work

TABLE 6 Summary of processes for implementing Industry 5.0

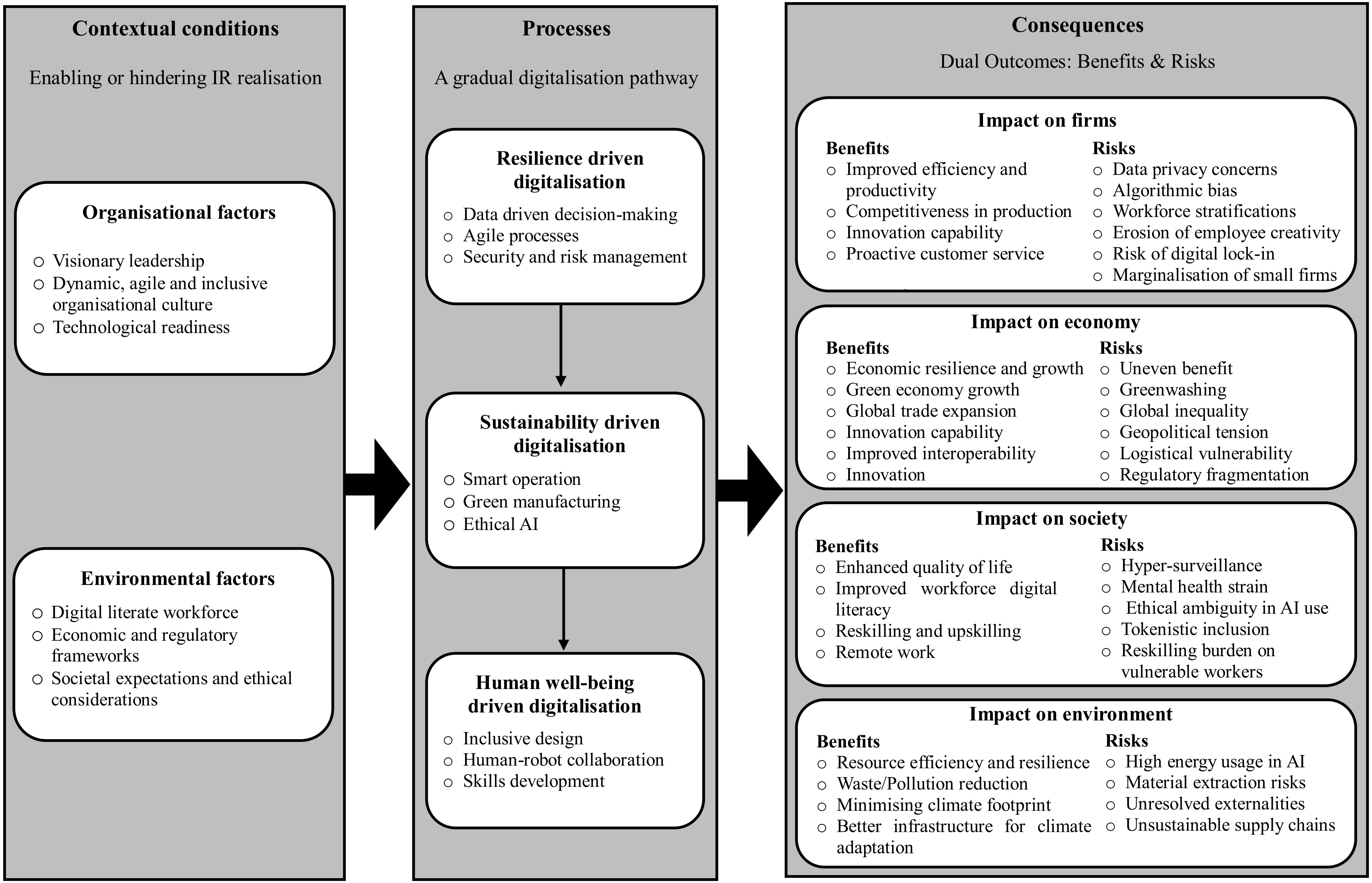
	Mechanisms	Description
Digitalisation to improve human well-being	Human-centric design and collaboration	Intelligent collaboration between human operators and properly designed machines, such as cobots, AR/VR, and exoskeletons, foster harmonizing human-machine interaction for enhanced efficiency and human roles.
	Personalisation and configuration	Develop flexible manufacturing systems and data-driven product development to allow manufacturers to develop products that meet individual customer preferences.
	Skills development system	Focus on reskilling and upskilling programmes for employees to enhance their digital literacy, data analytics, and human-machine collaboration skills.
Digitalisation to improve sustainability	Smart operation	Leverage AI, IoT, ML, digital twins, and edge computing for smart operations and decision-making, faster response times, and improved system reliability.
	Green manufacturing technologies	Implement green technologies, resource optimization, renewable energies, energy-efficiently used machinery, and sustainable materials to achieve sustainable production, as well as environmental sustainability.
	Ethical and inclusive design practices	Ensure ethical AI use, inclusive design, active CSR engagement, and sustainability practices that are accessible and beneficial to diverse user groups.
Digitalisation to improve resilience	Real-time data analytics, business intelligence (BI) systems, and AI-driven decision support	Utilize real-time analytics, BI systems, and AI through gathering, processing, and visualizing data to support strategic planning for better decision-making.
	Agile process and system	Adopt agile methodologies, using agile manufacturing to allow for rapid configuration and adaption to environmental changes.
	Security and risk management	Strengthen cybersecurity measures and develop robust risk management frameworks through human-machine collaboration.

Source: Authors own work

TABLE 7 Summary of Industry 5.0 Consequences

Impact	Impact area	Benefits	Risks
Firms	Operational efficiency and productivity	Enhanced automation and human-robot collaboration, real-time data analytics, and achieving employee satisfaction and retention.	Data privacy concerns from wearables; surveillance; algorithmic bias; workforce stratification.
	Competitiveness	Precision in production, supply chain transparency, enhanced innovation capability, improved product quality, personalised customer interactions, and proactive customer service.	Overdependence on automation; erosion of human creativity; exclusion of digitally limited firms.
	Business models	Shift to service-oriented models, subscription services, or pay-per-use frameworks.	Increased complexity; risk of digital lock-in; marginalisation of small or analogue firms.
Economy	Economic resilience and growth	Firm-level efficiency scales to national economic growth and resilience to disruptions.	Uneven benefits; potential for widening global inequality; SME exclusion.
	Green economy growth	Advances in green tech, sustainable production, and cleaner workplaces.	Greenwashing; energy-intensive 'green' tech; lifecycle sustainability unclear.
	Global trade and economic interconnectivity	Efficient, resilient supply chains; global market access; supply chain transparency.	Digital divide between high- and low-income regions; logistical vulnerabilities.
	Global standards	Improved interoperability, data exchange, and ethical tech standards.	Geopolitical tension over tech standards; regulatory fragmentation.
Society	Enhanced quality of life	Safer, ergonomic work; well-being technologies; personalised healthcare.	Hyper-surveillance; mental health strain; ethical ambiguity in AI applications.
	Social inclusivity and equality	Accessible tech for disabled users; digital literacy; reduced divide.	Marginalised communities may lack access to enabling infrastructure; tokenistic inclusion.
	Job transformation and workforce development	New high-skill roles; remote work; emphasis on reskilling.	Job losses in routine work; reskilling burden on vulnerable workers.
Environment	Maintaining sustainable resources	Optimised use of water, materials, and energy; waste reduction.	High energy usage in AI/AM systems; material extraction risks.
	Minimising the environmental footprint	Eco-design, green manufacturing, reduced pollution.	Carbon footprint of data centres and AM; unsustainable supply chains.
	Climate resilience	Infrastructure for climate adaptation and disaster resilience.	Increased e-waste; climate risk if not well regulated.

Source: Authors own work



FIURE 1 Contextual Conditions-Processes-Consequences of Industry 5.0

Source: Authors own work

Contextual conditions

Organisational factors

Visionary leadership

- Leadership and strategic decision-making (e.g., Cillo et al., 2022*; Grosse, 2024**; Mukherjee et al., 2023**)

Digital literate workforce

- Skill development system (e.g., Liu and Zhu, 2022**)
- Human-machine interaction skills (e.g., Ordieres-Meré et al., 2023*)

Technological readiness

- Advanced digital technologies (e.g., Aydin et al., 2023*; Caggiano et al., 2023*; Dahlke et al., 2024*; Dolgui and Ivanov, 2023*; Sharma et al., 2022**; Yin and Yu, 2022**)
- Digital infrastructure and facilities (e.g., Karmaker et at., 2023**; Kumar and Mallipeddi, 2022*; Rani and Srivastava, 2024**)

Dynamic organisational culture

- Dynamic organisational culture (e.g., Scaliza et al., 2022**)

Environmental factors

Economic and regulatory frameworks

- Incentives and funding (e.g., Ghobakhloo et al., 2023b*; Pistolesi et al., 2024**)
- Regulatory compliance framework (e.g., Ghobakhloo et al., 2023a*)
- Strong market demand (Karmaker et al., 2023**; Scuotto et all, 2023**)

Societal expectations and ethical considerations

- Societal expectations (e.g., Sharma et al., 2022**; Ejaz, 2023*)
- Ethical issues of AI and data use (e.g., Carayannis et al., 2023*; Carayannis et al., 2022*; Garbowska et al., 2022**; Gagnidze, 2023**; Pistolesi et al., 2024**)

Processes

Digitalisation with a focus on resilience

Enhanced decision-making and data utilisation

- Real-time data analytics (e.g., Ordieres-Meré et al., 2023*)
- Business intelligence system (e.g., Sharma et al., 2022**; Wang et al., 2023*)
- AI-driven decision support (e.g., Sharma et al., 2022**)

Agile processes

- Agile methodologies (e.g., Peltokorpi et al., 2023**)
- Change management (e.g., Grosse 2024*)

Security and risk management

- Robust cybersecurity measures (e.g., Kumar and Mallipeddi, 2022*; Rani and Srivastava, 2024*)
- Risk management framework (e.g., Peruzzini et al., 2023**)
- Disaster recovery and business continuity (e.g., Agrawal et al., 2023*; Enang et al., 2023*; Qahtan et al., 2022*)

Digitalisation with a focus on human well-being

Human-centric design and collaboration

- Human operators and machines collaboration (e.g., Caggiano et al., 2023*; Grybauskas and Cárdenas-Rubio, 2024*)
- Human-machine system (e.g., Caryannis et al., 2023*; Caryannis et al., 2021b*)

Personalisation and configuration

- Flexible manufacturing system (e.g., Jiménez-Partearroyo et al., 2023**)
- Data-driven product development (e.g., Cutrona et al., 2023*)

Skills development

- Reskilling and upskilling programs (e.g., Panagou et al., 2023*)

Digitalisation with a focus on sustainability

Smart operation

- Artificial intelligence (AI) and machine learning (ML) (e.g., Ahemd et al., 2023**; El-Brawany et al., 2023**; Liao et al., 2023**)
- Internet of things (IoT) and edge computing (e.g., Yao et al., 2022**)
- Digital twins (e.g., Barata and Kayser, 2024**; Curtona et al., 2023*; Ejaz, 2023*; Ivanova 2023*)

Green manufacturing technologies

- IoT-based cloud-assisted green manufacturing technologies (e.g., Caiazzo et al., 2023*)
- AI and additive manufacturing (e.g., Qahtan et al., 2022*; Sharma et al., 2022**)
- Optimize resource consumption (e.g., Destouet et al., 2023*)

Ethical and inclusive practices

- Ethical guidelines (e.g., Wang et al., 2023*)
- Sustainability practices (e.g., Cutrona et al., 2023*)
- Accessible and beneficial design practices (e.g., Aydin et al., 2023*; Battini et al., 2022**)

Consequences

Impact on firms

Operational efficiency and productivity

- Collaborative robots and advanced automation (e.g., Ordieres-Meré et al., 2023*)
- Real-time data and analysis (e.g., Ordieres-Meré et al., 2023*)
- Improved employee satisfaction (e.g., Psarommatis et al., 2023*)
- Efficiency in logistics (e.g., Agrawal et al., 2023*)

Improved competitiveness

- Aigle and flexible manufacturing (e.g., Huang et al., 2024**; Ordieres-Meré et al., 2023*)
- Supply chain transparency (e.g., Peruzzini et al., 2023**)
- Enhanced innovation capabilities (e.g., Carayannis et al., 2023*; Carayannis et al., 2021*)
- Improved product quality (e.g., Peruzzini et al., 2023**)
- Personalized customer interactions (e.g., Sharma et al., 2022**; Nayeri et al., 2023*; Pistolesi et al., 2024**)
- Proactive customer service (e.g., Lazić et al., 2023*; Roy et al., 2023**)

Strategic changes

- Business model innovation (e.g., Hussain et al., 2023**)

Impact on environment

Maintaining sustainable resources

- Resource optimization (e.g., Agrawal et al., 2023*; Psarommatis et al., 2023*)
- Digital twins for ecosystems (e.g., Cutrona et al., 2023*)
- Waste reduction (e.g., Qahtan et al., 2022*; Sharma et al., 2022**)

Minimising environmental footprint

- Eco-friendly product design (e.g., Yuan et al., 2022**)
- Green manufacturing technologies (e.g., Caiazzo et al., 2023*)
- Reduced industry pollution (e.g., Qahtan et al., 2022*)

Achieving climate resilience

- Environmental preservation and climate change mitigation (e.g., Agrawal et al., 2023*; Psarommatis et al., 2023*)
- New environment protection laws (e.g., Gagnidze, 2023**)

Impact on economy

Economic resilience and growth

- Reduction in operational costs, increase efficiency (e.g., Ordieres-Meré et al., 2023*)
- Enhanced operational efficiency productivity (e.g., Pistolesi et al., 2024**)

Cultural of continuous innovation

- Integration of digital innovation (e.g., Lu et al., 2022*)

Green economy

- Green economy growth (e.g., Caiazzo et al., 2023*)

Global trade and economic interconnectivity

- Efficient and resilient global supply chain (e.g., Sindhwani et al., 2022**)
- Global economic interconnectivity (e.g., Peruzzini et al., 2023**)

Global standards

- Global standards (e.g., Agrawal et al., 2023*)

Impact on society

Enhanced quality of life

- Improved work conditions (e.g., Cho et al., 2022*)
- Personalized products and services (e.g., Nayeri et al., 2023*; Pistolesi et al., 2024**)
- Health and well-being (e.g., Aydin et al., 2023*; Cillo et al., 2022*; El-Brawany et al., 2023**; Helm et al., 2023**; Qahtan et al., 2022*; Pasparakis et al., 2023**)

Social inclusivity and equality

- Accessible technologies (e.g., Peltokorpi et al., 2023**)
- Reducing digital divide (e.g., Panagou et al., 2023*)
- Empowering marginalized groups (e.g., Cillo et al., 2022*)

Job transformation and workforce development

- Increased remote work (e.g., Lu et al., 2023*)
- Creation of new jobs (e.g., Cutrona et al., 2023*; Liao et al., 2023*)
- Reskilling and upskilling (e.g., Grosse 2023*; Pasparakis et al., 2023**)
- Continuous learning (e.g., Dornelles et al., 2023*; Hussain et al., 2023**)

FIGURE 1 Contextual Conditions, Processes and Consequences of Industry 5.0

Note:

* *denote a conceptual study*

** *denote an empirical study*

Source: Authors own work