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Industry 5.0 implications for inclusive sustainable manufacturing: An evidence-knowledge-based strategic roadmap

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ABSTRACT

Despite the hype surrounding Industry 5.0 and its importance for sustainability, the micro-mechanisms through which this agenda can lead to socio-environmental values are largely understudied. The present study strived to address this knowledge gap by developing a strategic roadmap that outlines how Industry 5.0 can boost sustainable manufacturing. The study first conducted a content-centric literature review and identified 12 functions through which Industry 5.0 can inclusively boost sustainable manufacturing. The study further developed a strategic roadmap that identified the complex contextual relationships among the functions and explained how they should be synergistically leveraged to maximize their contribution to sustainability. Results reveal that value network integration, sustainable technology governance, sustainable business model innovation, and sustainable skill development are the most driver and tangible implications of Industry 5.0 for sustainable manufacturing. Alternatively, renewable integration and manufacturing resilience are among the most dependent and hard-to-reach sustainable functions of Industry 5.0, and their materialization requires major strategic collaboration among stakeholders. The strategic roadmap outlines how Industry 5.0 stakeholders can leverage the technological and functional constituents of this agenda to promote sustainable manufacturing inclusively.

1. Introduction

Sustainable manufacturing is a dynamic concept, meaning its scope and implication evolve with sustainability priorities and socio-environmental developments (Machado et al., 2020). Sustainable manufacturing was first understood as a means for minimizing the negative impacts of manufacturing operations on the environment. Nonetheless, it is nowadays regarded as an inclusive initiative needed for promoting sustainability's economic, environmental, and social dimensions (Malek and Desai, 2020). The literature acknowledges that technological innovations and their industrial applications may align with the core objectives of sustainable manufacturing (Enyoghasi and Badurdeen, 2021). Recent studies revealed that the digital transformation of the manufacturing industry, known as Industry 4.0, may promote some aspects of sustainability (Ching et al., 2022). Industry 4.0 enables manufacturers to promote their industrial operations' microeconomic and environmental sustainability implications (Machado et al., 2020). Examples of such Industry 4.0's implications may include the reduction of waste, energy consumption, or emission, thanks to the cleaner operations enabled by innovative technologies like the industrial internet of things (IIoT) and additive manufacturing (Qi et al., 2023). Although Industry 4.0 may positively affect sustainability at the microscopic (firm-level) analysis level (Malek and Desai, 2020), its implications for socio-environmental sustainability, particularly at the macroscopic (industry) analysis levels, have been controversial (Ghobakhloo et al., 2023a). Indeed, Industry 4.0 and the misgovernance of its technologies, such as artificial intelligence (AI) and robotics, have

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Nomenclature

Acronym	Definition
AI	artificial intelligence
CAI	Cognitive Artificial Intelligence
FRM	Final Reachability Matrix
ILB	Logic-knowledge Base
IRM	Initial Reachability Matrix
ISM	Interpretive Structural Modeling
MAP	Manufacturing strategic adaptability
MCR	Manufacturing circularity
MNR	Manufacturing resilience
MPD	Manufacturing productivity
MRS	Manufacturing responsiveness
NGT	Nominal Group Technique
RIT	Renewable integration
SBI	Sustainable business model innovation
SEP	Sustainable employment
SKD	Sustainable skill development
STG	Sustainable technology governance
VNI	Value network integration
WES	Work environment smartification

been detrimental to various socio-environmental aspects of sustainable manufacturing, including energy conservation, circularity, job displacement, and workplace dignity (Chiarini, 2021; Grybauskas et al., 2022; Kovacs, 2018). Because of these controversies regarding the implications of Industry 4.0 for sustainability, policymakers and academicians are already debating the need for a regulatory agenda called, Industry 5.0 to govern the disruptive force of Industry 4.0 (Sindhwani et al., 2022). The European Commission's policy briefs, which propagated the Industry 5.0 agenda in early 2021 and 2022, are a primary example of these movements toward regulating the controversial sustainability implications of Industry 4.0. Unexpectedly, European Commission has recently proposed that while Industry 4.0 is far from its peak maturity (Breque et al., 2021), this framework can no longer be considered appropriate for Europe's Industry of Future, where inclusive sustainability is an indispensable objective (Renda et al., 2022). Recent scientific studies have widely adopted this radical perspective and offered valuable insights into constituents, drivers, barriers, and readiness dimensions of this emerging agenda (Destouet et al., 2023; Hein-Pensel et al., 2023; Mukherjee et al., 2023).

As expected, the scientific community firmly believes in the sustainability values of Industry 5.0, and the scholarly literature offers early insights into how this agenda might promote sustainable development (Dwivedi et al., 2023; Ivanov, 2022). For example, Ivanov (2022) synthesized Industry 5.0 literature and theoretically highlighted some potential sustainability values of this agenda at the value network and societal level. Dwivedi et al. (2023) strived to identify the synergies between Industry 5.0 and the circular supply chain that might boost sustainability. In addition, recent studies offer an early understanding of how Industry 5.0 stakeholders, including governments, should leverage this agenda to materialize its sustainability values. Despite these early invaluable contributions, little has been done to understand how Industry 5.0 can inclusively promote sustainable manufacturing. One may question if the results of previous studies on the Industry 4.0-sustainable manufacturing interactions could be extended to Industry 5.0 research context to address this knowledge gap. Indeed, the sustainable manufacturing implications of Industry 4.0 are relatively well-studied (Dwivedi et al., 2022; Enyoghasi and Badurdeen, 2021; Ching et al., 2022). Generalizing the previous findings on Industry 4.0-sustainable manufacturing to the Industry 5.0 context is ill-advised for the following reasons. First, Industry 5.0 draws on human-centric and cognitive sets of technologies to deliver its intended values (Lu et al., 2022; Saadati and Barenji, 2023). Second, Industry 5.0 is a socio-politically pulled framework, whereas Industry 4.0 is primarily a productivity-driven and technology-push phenomenon (Golovianko et al., 2023; Xu et al., 2021a).

The present study addresses the following research gaps in light of the discussions above. First, Industry 5.0 is a broad and elusive concept with varying implications in different business contexts (Karmaker et al., 2023; Lo, 2023). While an operational definition of Industry 5.0 specific to the manufacturing context is essential for studying its potential contribution to sustainable manufacturing, such understanding is limited (Hein-Pensel et al., 2023). This critical knowledge gap prevents the focused investigation of Industry 5.0's specific characteristics and more profound knowledge of its influence within the manufacturing environment. Consistently, the study's first objective involves offering an operational definition of Industry 5.0 within the sustainable manufacturing context and developing an archetype that outlines an exemplary manifestation of Industry 5.0 hyper-connected manufacturing ecosystem, demonstrating its unique features.

The second knowledge gap concerns the opportunities that Industry 5.0 might offer for sustainable manufacturing. Building on the sustainability literature within (e.g., Atif, 2023; Ghobakhloo et al., 2023b), the present work proposes that Industry 5.0 can contribute to sustainable manufacturing through complex and intertwined functions. This assumption roots in the complex nature of technologies, design principles, and components of the Industry 5.0 ecosystem (Ghobakhloo et al., 2022). Nonetheless, the micro-mechanisms (functions) through which Industry 5.0 may promote various aspects of sustainable manufacturing are largely understudied. Without identifying such functions, businesses and social actors will struggle with leveraging Industry 5.0's potential for fostering sustainability in manufacturing, impeding the integration of sustainable digital practices that can guarantee long-term competitive advantage. Therefore, the study's second objective entails exploring and comprehending the sustainable manufacturing functions of Industry 5.0 that unlock its full potential and promote sustainable practices in the manufacturing environment. In line with this objective, the study conducts a content-centric review of Industry 5.0 literature and identifies the functions through which this agenda can inclusively promote sustainable manufacturing.

The third knowledge gap relates to the lack of a roadmap explaining how the Industry 5.0 actors should leverage these functions. Building on the Industry 4.0-sustainable manufacturing literature (e.g., Ching et al., 2022), it is expected that the sequential relationship and specific order in leveraging the sustainable manufacturing functions of Industry 5.0 have a critical impact on this agenda's sustainability outcomes. Unfortunately, the sustainable manufacturing literature lacks a strategic roadmap that defines this order. The lack of such a roadmap may cause manufacturers to struggle to prioritize and coordinate the functions, leading to a suboptimal implementation of Industry 5.0's framework for sustainable manufacturing. For this objective, the study draws on the Interpretive Structural Modeling (ISM) technique and the Interpretive Logic-knowledge Base (ILB) and develops a strategic roadmap that outlines how manufacturers should leverage Industry 5.0 sustainability functions to promote manufacturing sustainability values. The study integrated ISM and ILB as it allows seamlessly address the three fundamental steps required to develop such a strategic roadmap. As the first requirement for developing the strategic roadmap, it is essential to identify the precedence relationships among the system elements. Different decision modeling techniques like ISM, DEMATEL, and their fuzzy variants can satisfy this requirement. The second requirement relates to expert-based group decision-making, where experts engage in live discussions to generate a shared consensus on each pairwise relationship and its detailed implication (functionality). ISM is regarded as highly suitable for this requirement of strategy roadmapping since it supports the integration of small-group discussion techniques for such purposes, as widely acknowledged by previous research (e.g., Ching et al., 2022). The third requirement focuses on interpreting the identified contextual relationships. To fulfill this requirement, developing a knowledge base is essential, which entails recording and incorporating the collective opinions of experts regarding the functionality and implications of each pairwise relationship. The original ISM integrated with ILB satisfies this requirement most effectively (Ghobakhloo et al., 2022).

Considering the knowledge gaps and objectives discussed above, the study proposes and systematically answers the following research question.

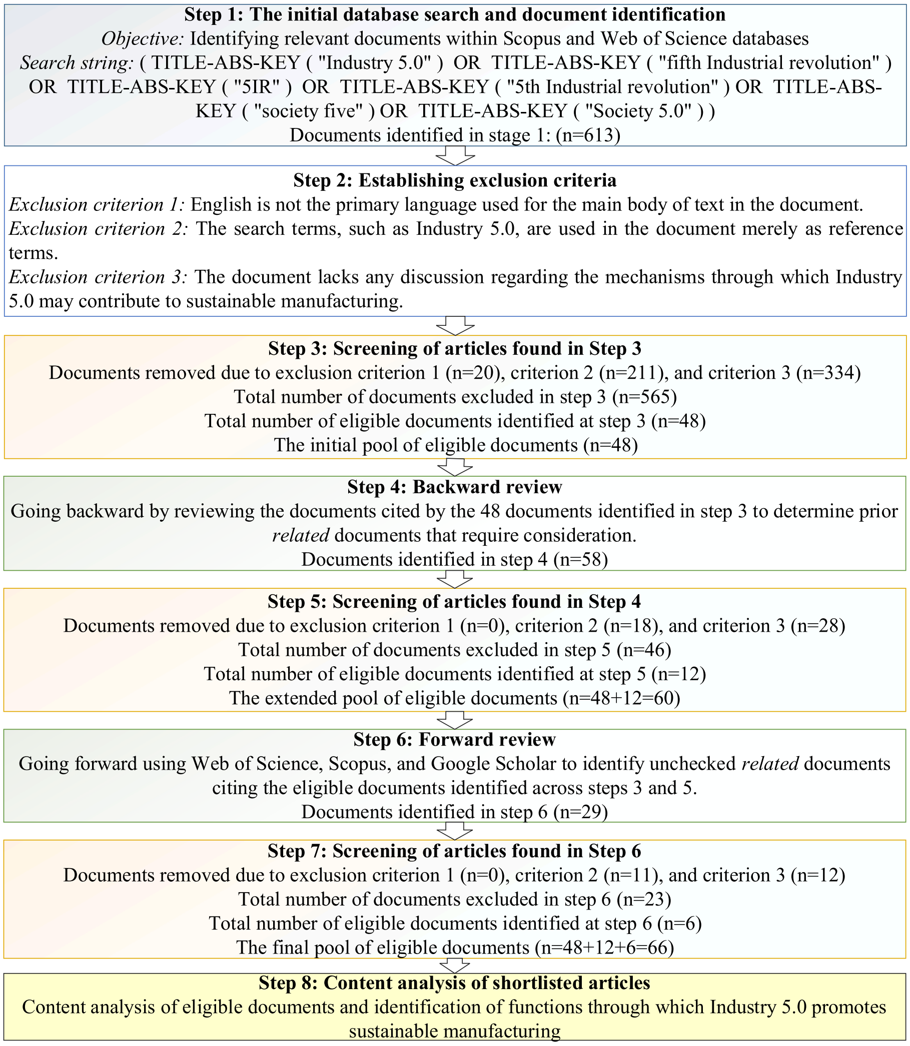
> *RQ:* How can Industry 5.0 agenda and the underlying technologies and functions promote sustainable manufacturing?

The novelty of the present work lies in offering an operational definition and archetype of Industry 5.0 specific to the sustainable manufacturing context. Secondly, it explores and identifies the sustainable manufacturing functions of Industry 5.0, which have been largely understudied. By scrutinizing these functions, the study empowers Industry 5.0 stakeholders to integrate sustainable digital practices and gain long-term competitive advantages while promoting socio-environmental values. Finally, the article develops a strategic roadmap by integrating ISM and ILB to outline the sequential relationship and specific order in leveraging the sustainable manufacturing functions of Industry 5.0. This roadmap explains how manufacturers and their stakeholders should prioritize and coordinate these functions to achieve optimal implementation of Industry 5.0 technologies and principles for sustainable manufacturing.

The remainder of the paper is structured as follows. The systematic review of Industry 5.0 literature is conducted in section two, in which the study offers the Industry 5.0 archetype and discusses its operational definition and sustainability functions. Section 3 discusses the roadmapping methodology, whereas results are presented in section four. Section five provides the discussions and introduces the promised strategic roadmap. Finally, section six discusses the implications and future directions.

2. Literature review

The study performed a content-centric review of Industry 5.0 scholarly and gray literature to provide a better understanding of this agenda and identify the functions through which it can improve sustainable manufacturing. In this study, the term *"function"* refers to the various capabilities, opportunities, and outcomes that manufacturing digitalization under Industry 5.0 agenda can provide to manufacturers. These functions are developed by integrating and utilizing advanced technologies and design principles of Industry 5.0. These functions can be strategic, such as the ability to optimize production processes and reduce waste, or technological, such as the use of AI and automation to enhance efficiency and accuracy. The functions can also lead to different



Step 1: The initial database search and document identification
Objective: Identifying relevant documents within Scopus and Web of Science databases
Search string: (TITLE-ABS-KEY ("Industry 5.0") OR TITLE-ABS-KEY ("fifth Industrial revolution") OR TITLE-ABS-KEY ("5IR") OR TITLE-ABS-KEY ("5th Industrial revolution") OR TITLE-ABS-KEY ("society five") OR TITLE-ABS-KEY ("Society 5.0"))
Documents identified in stage 1: (n=613)

Step 2: Establishing exclusion criteria
Exclusion criterion 1: English is not the primary language used for the main body of text in the document.
Exclusion criterion 2: The search terms, such as Industry 5.0, are used in the document merely as reference terms.
Exclusion criterion 3: The document lacks any discussion regarding the mechanisms through which Industry 5.0 may contribute to sustainable manufacturing.

Step 3: Screening of articles found in Step 3
Documents removed due to exclusion criterion 1 (n=20), criterion 2 (n=211), and criterion 3 (n=334)
Total number of documents excluded in step 3 (n=565)
Total number of eligible documents identified at step 3 (n=48)
The initial pool of eligible documents (n=48)

Step 4: Backward review
Going backward by reviewing the documents cited by the 48 documents identified in step 3 to determine prior *related* documents that require consideration.
Documents identified in step 4 (n=58)

Step 5: Screening of articles found in Step 4
Documents removed due to exclusion criterion 1 (n=0), criterion 2 (n=18), and criterion 3 (n=28)
Total number of documents excluded in step 5 (n=46)
Total number of eligible documents identified at step 5 (n=12)
The extended pool of eligible documents (n=48+12=60)

Step 6: Forward review
Going forward using Web of Science, Scopus, and Google Scholar to identify unchecked *related* documents citing the eligible documents identified across steps 3 and 5.
Documents identified in step 6 (n=29)

Step 7: Screening of articles found in Step 6
Documents removed due to exclusion criterion 1 (n=0), criterion 2 (n=11), and criterion 3 (n=12)
Total number of documents excluded in step 6 (n=23)
Total number of eligible documents identified at step 6 (n=6)
The final pool of eligible documents (n=48+12+6=66)

Step 8: Content analysis of shortlisted articles
Content analysis of eligible documents and identification of functions through which Industry 5.0 promotes sustainable manufacturing

Fig. 1. Content-centric literature review process to identify Industry 5.0's sustainable manufacturing functions.

outcomes, such as reducing environmental impacts, improving social and economic conditions, or creating new business opportunities. In essence, a function in this study refers to the beneficial effects that Industry 5.0 transformation and underlying practices can bring to manufacturers and their networks.

Content-centric literature review entails a comprehensive search and synthesizing of relevant literature and examining the themes, concepts, and theories presented in the relevant studies to understand the given research context thoroughly (Watson and Webster, 2020).

The content-centric review process undertaken is illustrated in Fig. 1, which involves nine steps. Step 1 involved defining the search terms and identifying potentially relevant documents by searching the Web of Science and Scopus databases. The search terms also included the keyword 'society 5.0′ because the literature widely ties Industry 5.0 to the Society 5.0 concept (Huang et al., 2022). Search efforts in Step 1 identified 613 unique documents. Step 2 involved defining exclusion criteria, as shown in Fig. 1. The 613 documents were subjected to exclusion criteria within step 3, removing 565 documents and establishing the initial pool of 48 eligible documents. A backward review of the 48 eligible documents in step 4 identified 58 new documents. In step 5, the exclusion criteria were applied to the 58 newly identified documents, and as a result, 12 new eligible documents were identified. By the end of Step 5, the extended pool of eligible documents consisted of 60 documents (48 + 12).

The forward review for identifying additional related documents citing the 60 eligible documents was conducted in step 6. In step 7, the exclusion criteria were applied to the 29 newly identified documents across step 6, leading to identifying six new eligible documents. At the end of step 7, the final pool of eligible documents included 66 documents (48 + 12+6 = 66).

In step 7, two content assessors separately scrutinized the content of each eligible document and performed the evidence synthesis. The assessors followed predefined measures to ensure the validity and reliability of the content analysis. Examples of these measures included following the standardized coding scheme, text denoising procedure, and collaborative disagreement tracking protocol.

VOSViewer was employed to gain bibliographic insights into the significance of topics explored within the literature on Industry 5.0, uncovering notable information and patterns regarding the relevance and prominence of various themes in the research context. Fig. 2 implies that the literature associates several technologies with Industry 5.0, most notably AI and IoT. Sustainable development, man-machine integration, and human-centric manufacturing are among the most acknowledged expected impacts of Industry 5.0. The Industry 5.0 literature pays particular attention to the issue of sustainability and efficiency in the energy context.

2.1. *Industry 5.0 archetype*

Industry 5.0 has been deeply inspired by Society 5.0, sharing a common ground in focusing on a human-centric approach, technological integration, cross-sector collaboration, and a shared vision of utilizing technology for a better future (Carayannis and Morawska-Jancelewicz, 2022; Ghobakhloo et al., 2023a, 2023b). The expansion from Society 5.0 to Industry 5.0 demonstrates the influence of the broader societal context on the industrial sector's transformation (Huang et al., 2022). Society 5.0 envisions a more comprehensive transformation leveraging technology for societal challenges and improved quality of life (Mourtzis et al., 2023), whereas Industry 5.0 adopts a more industrial transformation approach (Xu et al., 2021a, 2021b).

Despite the recent developments in Industry 5.0 scholarly literature, this phenomenon is still embryonic and evolving rapidly, and there is a lack of a universally agreed-upon definition or framework for Industry 5.0. Such vagueness hinders the ability to identify and interpret the sustainable manufacturing functions of Industry 5.0. Therefore, the study synoptically builds on the ongoing sociopolitical and scholarly discussions, such as the European Commission's policy briefs (Breque et al., 2021; Renda et al., 2022) and the recent works of Ghobakhloo

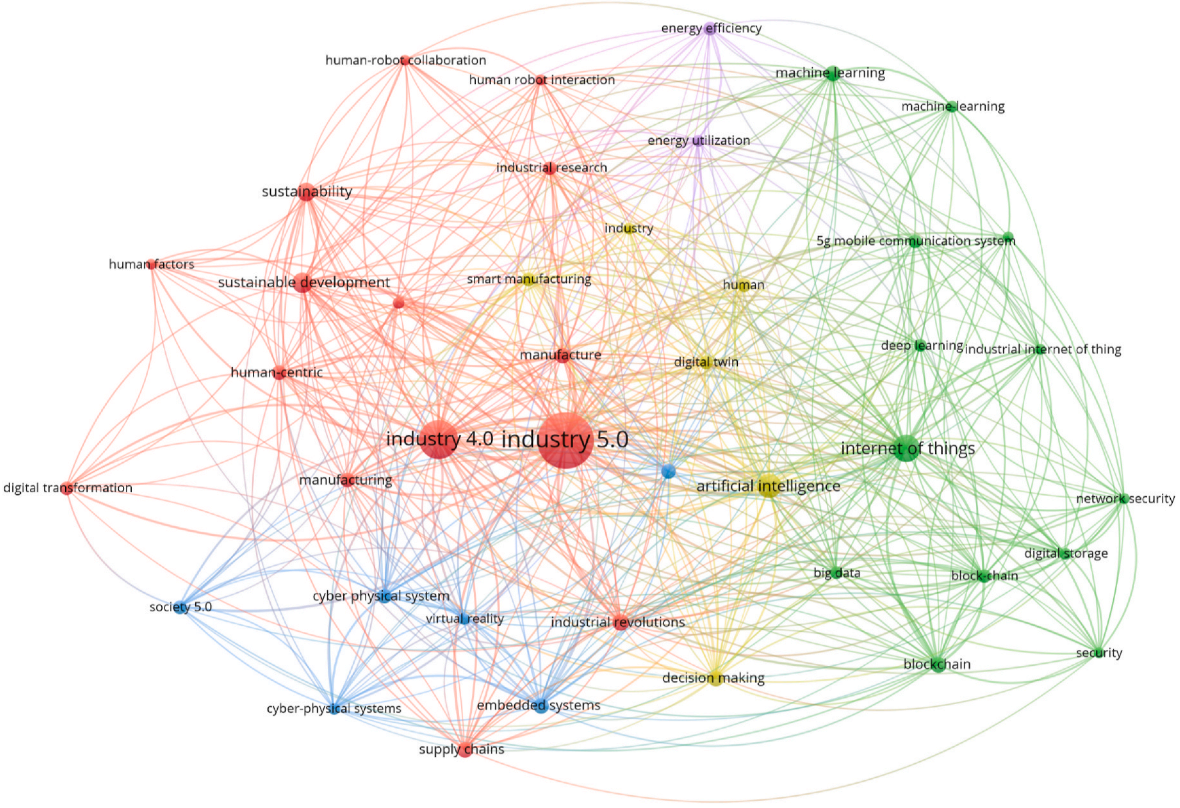


Fig. 2. Bibliometric analysis of keyword co-occurrence within Industry 5.0 context (Source: VOSViewer).

et al. (2023a) and Ivanov (2022) and operationalize the Industry 5.0 concept as governance agenda driven by society's needs, acknowledging the crucial role of technology-led digital transformation in achieving a sustainable industry of future. It strikes a balance between policies governing the digital transformation of Industry 4.0 and the potential emergence of a new industrial revolution fueled by advancements in novel technologies such as AI, particularly artificial general intelligence. Furthermore, the study introduces the architectural design of Industry 5.0 in Fig. 3. Notably, this archetype merely describes Industry 5.0 functionality within the manufacturing context.

The architectural design proposes that Industry 5.0 is not the next industrial revolution to replace Industry 4.0. Instead, Industry 5.0 represents the logical continuation of the existing digital industrial transformation, aiming to govern technological change and systematically address Industry 4.0 shortcomings on societal and ecological fronts. Therefore, the archetype in Fig. 3 proposes that Industry 5.0 builds on many features of Industry 4.0, such as large-scale integration of disruptive technological innovations or achieving valuable techno-functional design principles, to promote industrial productivity and socio-environmental values.

Fig. 3 implies that Industry 5.0 relies on the integration of many technologies, techno-functional principles, and smart components to achieve transformation toward a sustainable, productive, human-centric, and resilient future industry. The first layer of the archetype concerns the technological constituents of Industry 5.0 that drive digital industrial transformation. Under this layer, facilitating technologies refer to innovative information and operations technologies that have become significantly mature, standardized, accessible, and affordable during the past decade. Emerging technologies, as the name conveys, refer to emerging disruptive technological innovations such as Cognitive-like Artificial Intelligence (CAI) that are expected to redefine Industry norms and business rules in the near future (Ahmed et al., 2023). The properties of these technologies have been thoroughly discussed within the extant literature (e.g., Maddikunta et al., 2022; Saadati and Barenji, 2023).

The techno-functional principles of Industry 5.0 entail a set of technical and functional design principles indispensable to delivering the values that Industry 5.0 transformation promises. Due to their complexity, these principles are deeply challenging to achieve and significantly rely on the technological constituents of Industry 5.0 (Tiwari et al., 2022). Although Industry 5.0 shares most of these design principles with its predecessor, it considerably redefines the extent and scope of some design principles. For example, horizontal integration under Industry 4.0 entails the integration of operations and processes across the supply network, whereas horizontal integration under Industry 5.0 also involves the seamless integration of stakeholders (Ghobakhloo et al., 2023b). Besides smart factories, the digital industrial transformation under Industry 5.0 involves various smart components, such as smart customers and products, to deliver a hyper-connected business environment that empowers inclusive sustainability (Alexa et al., 2022; Ivanov, 2022).

Fig. 3 also conveys that the value layer of Industry 5.0 entails promoting sustainable development. Indeed, Industry 5.0 directly criticizes the profit-centricity of Industry 4.0, emphasizing that digitalization and underlying technologies should address the emergent concerns within the industrial, societal, and environmental landscape (Breque et al., 2021). Although inclusive sustainability is the core objective of Industry 5.0, economic resilience, circularity, and human-centricity are this agenda's most recognized sustainability values (Mourtzis et al., 2023).

The *resilience* principle of Industry 5.0 proposes that the contribution of the digital industry should extend beyond archetypal societal development goals such as equality or job creation (Breque et al., 2021). The industry should also morph into a resilient source of prosperity for all stakeholders in which value networks can withstand and recover from disruptions, challenges, and unexpected events. Resilience is a crucial aspect of Industry 5.0 because it recognizes the need for adaptability and responsiveness in the face of rapidly changing environments. Global crises such as the COVID-19 pandemic and unprecedented geopolitical changes (e.g., Russia's invasion of Ukraine) have proven the fragility of the existing approach to global value creation. Industry 4.0 and underlying digitalization have provided early adopters with the necessary flexibility and adaptability to cope with ongoing crises (Mahmoodi et al., 2022). Nonetheless, these opportunities have been primarily delivered to mega-corporations and tech giants that lead the digitalization race. While most Industry 4.0 leaders have thrived under the ongoing global crises and enjoyed unparalleled business growth, many

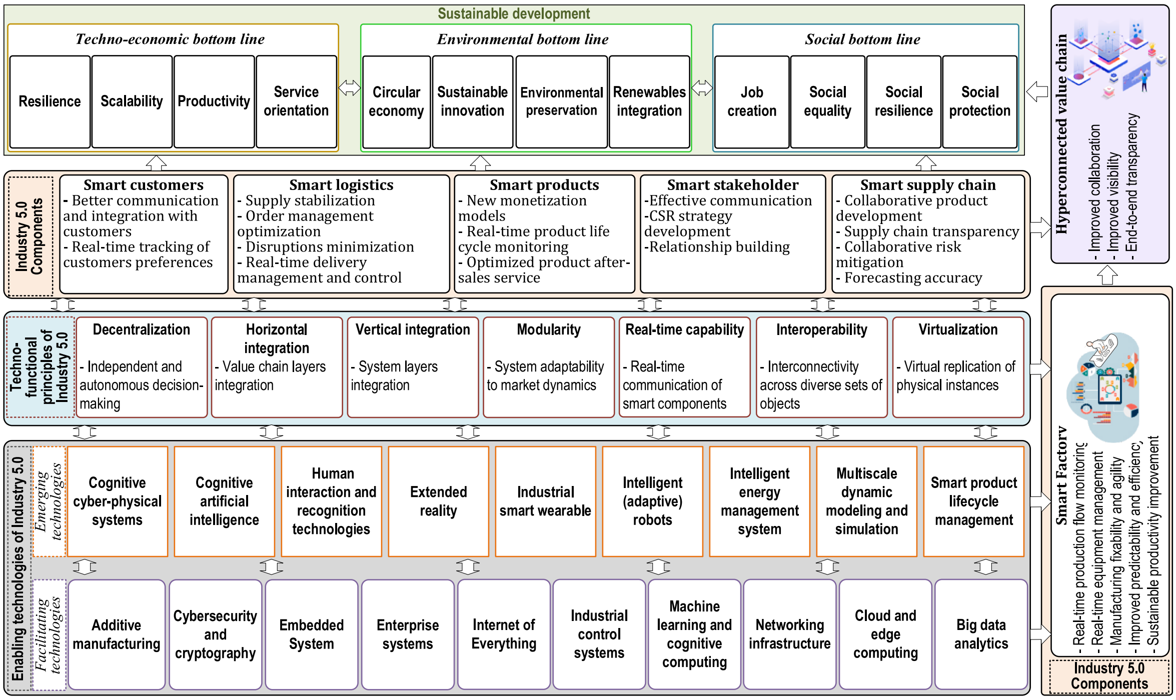


Fig. 3. Industry 5.0 archetype (source: authors).

smaller or less technologically advanced businesses struggle to survive under the disruptive force of the COVID-19 pandemic and the digital race (Stentoft et al., 2021). The resilience principle of Industry 5.0 proposes that digitalization should offer equal opportunities for value chain resilience so businesses can progress toward more flexible processes and adaptable production capacity (Breque et al., 2021; Ivanov, 2022). By doing so, most value chains would continue to operate and provide basic human needs, thus promoting societal resilience (Renda et al., 2022).

The *human-centricity* value objective of Industry 5.0 argues that there is a need to regulate the way businesses force their employees to adapt to the continually evolving technology (Nahavandi, 2019). Instead, there should be a healthy balance between human resources adapting to digitalization and digital technologies being purposefully used to adapt business processes according to employees' needs (Longo et al., 2020). This value objective proposes that digital technologies should serve society rather than contrariwise. For example, in manufacturing, human-centricity entails designing and deploying novel technologies, such as CAI or adaptive robots, that should center around labor preferences and well-being (Nahavandi, 2019).

The *circularity* objective of Industry 5.0 places the circular economy at the heart of industrial operations, urging the industry to adhere to planetary boundaries as an existential priority (Bednar and Welch, 2020). Since corporations should first thrive economically to afford to prioritize environmental sustainability, Industry 5.0 promotes the environmental-centric economic performance of industries. Scholars such as Golovianko et al. (2023) and Sharma et al. (2022) explain that the Industry 4.0 technology trends, such as AI, additive manufacturing, and digital twin technology, already have the capacity to promote resource efficiency, minimize waste, simplify the integration of cleaner energy, and facilitate cleaner production (Mourtzis, 2020). Nevertheless, Industry 5.0 stakeholders should devise and implement clear-cut industrial and political initiatives to ensure that emerging technologies are purposefully used for environmental preservation.

2.2. Industry 5.0 sustainable manufacturing functions

The content-centric review of the literature identified 12 functions through which Industry 5.0 can contribute to sustainable manufacturing. Each of the Industry 5.0 sustainability functions is briefly explained in the following.

Manufacturing strategic adaptability (MAP) refers to the manufacturers' ability to efficiently adjust their manufacturing operations and strategies to the changes in their external environment (Ahmed et al., 2022). MAP is indispensable to contemporary manufacturers due to the ever-increasing global disorders and disrupting forces (Favoretto et al., 2022). Industry 5.0 delivers the MAP in two ways. First, the analytical and intelligence capabilities associated with Industry 5.0 technologies allow manufacturers to get better insights into the market dynamics, improve decision processes, and enhance flexibility to change (Huang et al., 2022). Second, the technical assistance principle of Industry 5.0 can improve the culture of learning and development across functional departments, enhancing operational flexibility (Maddikunta et al., 2022).

Manufacturing circularity (MCR) denotes building and optimizing manufacturing systems to impact the environment less, be adjustable to changing material streams, promote recycling, and have less resource intensity (Schmitt et al., 2021). The implication of Industry 5.0 for MCR is multifaceted. It may involve integrating smart products that streamline life-cycle performance improvement (Xu et al., 2021a, 2021b). The stakeholder integration aspect of Industry 5.0 further ensures that manufacturers are committed to implanting new production models that favor circularity (Ghobakhloo et al., 2023a). Furthermore, Industry 5.0 technologies such as CAI, IEMS, and digital twin are critical for the manufacturing system optimization aspect of MCR (Leng et al., 2022; Maddikunta et al., 2022).

Manufacturing productivity (MPD) is inherent to digital manufacturing transformation under Industry 5.0 (Mukherjee et al., 2023). Indeed, Industry 5.0 technologies and principles offer numerous opportunities for addressing productivity gaps in the manufacturing environment (Xu et al., 2021a). For example, the continuous and autonomous asset monitoring capability provided by CCPS and IIoT can maximize equipment lifespan and enhance their effectiveness and performance (Liu et al., 2023). Alternatively, the technical assistance principle enhances seamless collaboration, eliminates information gaps, and reduces human errors, leading to improved employee productivity (Carayannis et al., 2021). The horizontal integration principle of Industry 5.0 further allows manufacturing partners to address the ever-increasing complexity of production models and global supply networks, alleviating productivity-damaging risks and disruptions (Ivanov, 2022).

Manufacturing resilience (MNR) refers to the manufacturers' ability to react to the disorders as quickly and efficiently as possible and promptly recover from disruptions or difficulties. The Industry 5.0 agenda may offer multiple opportunities for MNR. The decentralization and modularity principles of Industry 5.0 introduce agility into the foundation of production management, allowing manufacturing to ramp up throughput, adjust product mix, and recreate operations (Huang et al., 2022; Sindhwani et al., 2022). Industry 5.0 further offers inclusive visibility into manufacturing supply chain operations, identifying risk, bottleneck, and failure points, particularly via improved supply chain collaboration, process integration, and data democratization (Ivanov, 2022; Modgil et al., 2023). In addition, blockchain and digital twin-driven advancements can significantly enhance organizational resilience under the Industry 5.0 scenario. The smart contract enabled by the digital twin can act as a multi-agent system for peer-to-peer negotiation and coordination of tasks, boosting real-time monitoring, coordination, and adaptive decision-making within manufacturing processes (Leng et al., 2023a). This technology helps businesses respond quickly to disruptions, adapt to changing circumstances, and recover effectively. Blockchain can be further used in constructing a digital twin of a decentralized autonomous production system that can significantly boost manufacturing resilience (Leng et al., 2023b).

Manufacturing responsiveness (MRS) refers to the manufacturer's ability to develop and implement production methods that are agile, lean, and predictive. The core objective of MRS is to ensure corporate competitiveness under turbulent business environments by improving cost-effectiveness and the scalability of manufacturing processes (Kim et al., 2013). Industry 5.0 enhances the MRS in myriad ways. The integration and real-time capabilities of Industry 5.0 allow manufacturers to break the functional silos across the supply chain, obtain a real-time overview of market demand, and adapt to the produce-to-order production approach while maintaining productivity and cost-effectiveness (Sharma et al., 2022). Besides providing total visibility into the entirety of the product life-cycle, modularity and decentralization principles of Industry 5.0 can boost MRS by broadening the product portfolio and enhancing manufacturing flexibility while minimizing production costs (Coronado et al., 2023; Destouet et al., 2023).

Renewable integration (RIT) concerns integrating renewable energy sources into manufacturers' energy supply to strengthen cleaner production. While renewables are highly valued from the emission and environmental degradation reduction standpoint, their integration into the industrial supply chain is deeply challenged (Sinsel et al., 2020). In that vein, Industry 5.0 may offer important implications for addressing barriers challenging RIT. First, RIT within the manufacturing context relies on the balance between energy supply and demand across the power grid. The integrability and intelligence features of Industry 5.0 promote the integration of smart microgrids across the manufacturing processes and offer a real-time overview of renewable energy generation, as well as energy generation and demand forecasts (ElFar et al., 2021; Fraga-Lamas et al., 2021). Besides enhancing power grid flexibility and the integrability of renewable energy systems, the stakeholder-centricity of Industry 5.0 may expedite the prioritization of RIT across the manufacturing supply chains (Dwivedi et al., 2023).

Sustainable business model innovation (SBI) denotes manufacturers' ability to conceptualize innovations that align with sustainability goals and implement them into various blocks of their business model, such as key operations, value propositions, or revenue streams (Geissdoerfer et al., 2018). Industry 5.0 offers countless implications for SBI since each of the underlying technologies and principles could sustainably innovate various aspects of the business model. For example, servitization and the introduction of individualized smart products under Industry 5.0 fundamentally innovate the value propositions and customer-relationship elements of the business model while boosting critical aspects of inclusive sustainable manufacturing such as product life-cycle, customer experience, and product circularity (Dwivedi et al., 2023; Mourtzis, 2021). Alternatively, Industry 5.0 streamlines stakeholder-wide collaboration on sustainable open innovation and promotes sustainable innovation orientation of manufacturers and technology providers (Yin and Yu, 2022), leading to more sustainable product and process innovation capabilities (Aslam et al., 2020; Huang et al., 2022).

Sustainable employment (SEP) is multifaceted and concerns work and employment strategies that support people to have stable, enduring, and satisfying jobs. Industry 4.0 has been somewhat detrimental to various aspects of SEP, such as employee privacy as well as job security, displacement, and polarization (Grybauskas et al., 2022). The technical assistance principle and human-centricity of Industry 5.0 ensure that the digital transformation of the work environment within manufacturers is pulled by human needs instead of being pushed by technological advancements (Nahavandi, 2019). It means that instead of rapidly adapting the human workforce and the work environment to technological advances, technologies should be tailored to the needs and preferences of the human workforce under the Industry 5.0 agenda (Longo et al., 2020). It explains why human-centered technologies that favor SEP, such as adaptive robots, industrial smart wearables, cognitive cyber-physical systems, and extended reality, are among the technological constituents of Industry 5.0 (Leng et al., 2022; Saniuk et al., 2022).

Sustainable skill development (SKD) is bi-dimensional. The first dimension concerns manufacturers having the necessary knowledge and skills to progress in sustainable manufacturing. Under Industry 5.0, AI, extended reality, and smart wearables can allow businesses to develop individualized training and carrier development programs that boost employees' sustainability knowledge and expertise aligned with the core values of sustainable manufacturing (Leng et al., 2022; Nahavandi, 2019). The second dimension of SKD involves the necessary upskilling and reskilling to maintain existing employees relevant to the new realities of the digitalized and hyper-connected business environment. This dimension is critical to work sustainability. Industry 5.0 promotes this dimension via prioritizing human-centricity and actively seeking the involvement of stakeholders such as labor unions in the governance of manufacturers' technological transformation, which boosts commitment to the needed upskilling and reskilling (Cillo et al., 2022; Maddikunta et al., 2022).

Sustainable technology governance (STG) concerns integrating sustainability values into the process of exerting administrative and sociopolitical authority in the design, development, deployment, and operation of new technological innovation across the business and society (OECD, 2023). STG represents a collaborative effort from the government, social actors, civic society representatives, corporations, and customer communities to shape a new technology and its benefits and risks (Cullen-Knox et al., 2017; Hardin-Ramanan et al., 2018). Industry 5.0 can draw on its stakeholder-centricity and integration principles to address the challenges and complexity of STG. For example, Industry 5.0 can alleviate the Collingridge effect by deploying a seamless technology performance measurement system that reduces the delay between introducing new technology and realizing its societal impacts so that the intervention in the trajectory of technological innovation can be applied with minimum delay (Ghobakhloo et al., 2023b). From the technical perspective, Industry 5.0 can promote the development of more sustainable digitalization tools, such as ethical AI or human-centric cyber-physical systems, effectively harnessing the potential of these technologies to promote autonomy and sustainability within the industrial ecosystems. Furthermore, through promoting multi-stakeholder dialogues, knowledge sharing, and cooperative decision-making processes, Industry 5.0 can facilitate inclusive and participatory technology governance models that can lead to more trustworthy technological tools (Leng et al., 2021). An example of such technology governance implication can be seen in the cases of opportunities that Makerchain (a novel decentralized blockchain-driven model) (Leng et al., 2019) can offer for social manufacturing under Industry 5.0.

Value network integration (VNI) denotes that all stakeholders' information and operations technologies should be able to exchange information when required seamlessly (Ching et al., 2022). VNI is a function of the hull-mark design principles of Industry 5.0, namely, vertical integration, horizontal integration, and interoperability (Xu et al., 2021 a,b(Xu et al., 2021 a,b). Vertical integration ensures that all the processes and their underlying components across all core and support functions of the business unit can seamlessly communicate and exchange information (Alexa et al., 2022). Alternatively, the horizontal integration principle of Industry 5.0 enables the value network-wide integration of all vertically integrated functional processes of value chain members (Ivanov, 2022). The interoperability principle of Industry 5.0 ensures that industrial systems and their micro components of core and support functions throughout the value network can meaningfully and reliably communicate (Ghobakhloo et al., 2022). Since Industry 5.0 entails the smartification of all business environment components (including smart customers), the scope of VNI spans the entire stakeholder engagement spectrum (Carayannis and Morawska-Jancelewicz, 2022).

Work environment smartification (WES) refers to using digital technologies that allow employees to work more efficiently, productively, and safely (Wang et al., 2023). WES is inherent to Industry 5.0 since this agenda seeks to promote human-centricity as one of its core objectives (Nahavandi, 2019). Indeed, the technical assistance principle of Industry 5.0 entails using smart workplace technologies such as industrial smart wearables, cognitive robots, engagement applications, and CCPS to automate repetitive/dangerous tasks and improve employees' ability to make informed and data-driven decisions (Huang et al., 2022: Longo et al., 2020). Under Industry 5.0, WES's ultimate goal entails tailoring technologies to the needs of employees, allowing them to work smarter, faster, and more efficiently without compromising their autonomy and psychology (Coronado et al., 2022; Lu et al., 2022).

3. Research methodology

The core objective of the study is to develop a strategic roadmap that explains how the Industry 5.0 agenda and the underlying technologies and functions promote sustainable manufacturing. In general, a strategic roadmap is a reference document that visually assists actors in understanding the design of the transformation framework for a given phenomenon. To this purpose, the strategic roadmap should identify and describe the underlying actions and activities, their relational organization, and the functionality of their interactions that might satisfy the objectives of the transformation phenomenon. For this research, the synthesis of Industry 5.0 literature identified 12 actions and activities (functions) through which Industry 5.0 may promote sustainable manufacturing. Next, ISM was used to identify the relational organization of the functions and drew on ILB to understand the functionality of the interactions among the Industry 5.0 sustainable manufacturing functions. This section describes the execution of ISM.

ISM is a robust decision-support analytic tool that offers a structured system for understanding the operations of a complex system and its underlying mechanisms (Ching et al., 2022). Compared to alternative decision-making tools and techniques, ISM is most suitable for this study since it enables systematically exploring and understanding the sequential relationships between the sustainable manufacturing functions of Industry 4.0 as well as their relative importance. ISM has been extensively applied to the comparative research context, such as the study of Industry 4.0 sustainable innovation implications and enabling role of Industry 4.0 for circular supply chains (Faisal, 2023), which supports the decision to use this technique for strategic roadmapping. Following the mainstream literature, the underlying steps for performing ISM have been shown in Fig. 4.

The most preliminary step in applying ISM involves collecting the experts' opinions on the inclusiveness of the 12 sustainable manufacturing functions of Industry 5.0 (identified via literature review) and their interrelationships. The study only approached European experts since an H2020 project funded the present study, and the research consortium mainly prioritized a European perspective on the Industry 5.0 phenomenon. A detailed expert identification framework was applied to ensure that the participating experts were knowledgeable about Industry 5.0, had significantly contributed to digitalization-sustainability scholarly literature, and had sheer practical experience in related fields such as Industry 4.0/5.0, circular economy, and social sustainability.

In partnership with the research consortium, the research team collaborated to identify a group of potentially qualified experts. After careful consideration, the research team successfully identified a pool of 19 individuals who met the criteria for eligibility. To ensure that these experts were genuinely interested and prepared to participate, the research team took the initiative to reach out to them and provided each expert with a self-assessment questionnaire to evaluate their readiness and willingness to engage in the project. The questionnaire served as a tool to gauge experts' level of interest, expertise, and availability. By administering the self-assessment questionnaire, the research team aimed to gather valuable insights and information from the experts themselves. This approach facilitated gathering data on their qualifications, experience, and overall commitment, enabling the research team to make informed decisions about their potential involvement in the project. At the end of the expert selection process, ten eligible experts agreed to participate in the research.

The experts represented a diverse group of four females and six males, all academicians with extensive engagement experience in European projects, holding various roles, such as policy advisors or principal investigators. Their areas of expertise mainly encompassed manufacturing digitalization and sustainability. The experts had a wide range of experience, with over 15–25 years of experience in digitalization, smart manufacturing, product development strategies, technological innovation dynamics, green technology platforms, and sustainable digital transformation. Their academic backgrounds varied from logistics and operations management or complex systems and spatial planning to production engineering.

Expert panel meetings were managed using the Nominal Group Technique (NGT), a popular small-group discussion technique that systematically allows participants to reach a consensus regarding the topic of interest (Harvey and Holmes, 2012). The research team followed existing guides and examples to ensure the reliable application of NGT. The first NGT-based expert panel meeting revolved around experts revising and confirming the functions. The pairwise relational comparison of the functions and the interpretation of the relationships were performed across meetings 2 and 3.

4. Results

Step 1 of ISM involves building the contextual relationship among each pair of sustainability functions based on experts' collective opinions. Table 1 represents the contextual relationships among each pair of Industry 5.0 sustainable manufacturing functions, as defined by symbols described below:
V: Function *i* causes function *j*;
A: Enabler *i* is caused by function *j*:
X: Functions *i* and *j* mutually cause each other;
O: Functions *i* and *j* are independent

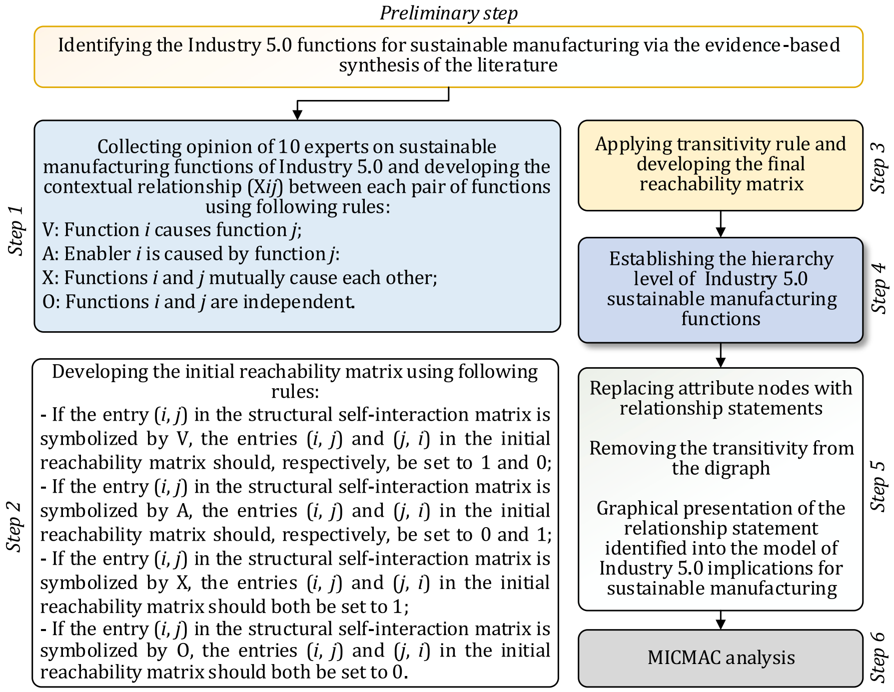


Fig. 4. Steps for performing ISM.

Table 1
The contextual relationships among functions.

functions		*j*											
		MAP	MCR	MPD	MNR	MRS	RIT	SBI	SEP	SKD	STG	VNI	WES
i	MAP	-	O	V	O	V	O	O	O	O	O	O	A
	MCR		-	V	V	O	V	A	O	A	A	A	O
	MPD			-	V	O	O	A	V	O	O	O	A
	MNR				-	A	A	O	A	O	O	A	O
	MRS					-	O	O	O	O	O	A	O
	RIT						-	A	O	A	A	O	O
	SBI							-	V	O	X	A	V
	SEP								-	A	A	O	O
	SKD									-	O	O	V
	STG										-	A	V
	VNI											-	O
	WES												-

Step 2 in applying ISM involves establishing the Initial Reachability Matrix (IRM). Following the transformation rules explained in Fig. 4, the IRM of the study is developed as Table 2. For example, the MAP-MCR entry in Table 1 has been symbolized as O. Therefore, both MAP-MCR and MCR-MAP entries in Table 2 are set to 0.

Step 3 entails developing the Final Reachability Matrix (FRM) by subjecting the IRM to the transitivity rule. Transitivity implies that when function A causes function B, and B causes C, function A necessarily causes function C, even though they might be directly independent. Table 3 represents the FRM for the present study, in which 1* reflects the presence of transitivity. For instance, the MAP-MNR entry in FRM is 1*. Referring to Table 2, MAP does not directly cause MNR. However, MAP causes MPD (MAP-MPD entry in IRM is 1), and MPD causes MNR (MNR-MPD entry in IRM is 1), introducing MAP as an indirect cause of MNR. Table 3 also lists each function's dependence and driving powers, indicating how many functions a given function causes and is caused by.

Step 4 in ISM concerns determining the hierarchy level of Industry 5.0 sustainable manufacturing functions. This process is performed iteratively by identifying all functions' reachability, antecedent, and intersection sets. The reachability set corresponds to the driving power, reflecting the functions caused by the given function. Alternatively, the reachability set corresponds to the dependence power, reflecting the functions that cause the given function. The intersection of the two sets constructs the intersection set. The hierarchy levels are identified based on the extraction sequence, which involves identifying functions with identical reachability and intersection sets and removing them from the reoccurring iterations. This extraction process continues until the extraction sequence of all functions is identified iteratively. Table A1 (in the appendix) shows the hierarchy level of all functions. For example, in iteration 1, MNR is the only function with identical reachability and intersection sets. Therefore, MNR has been excluded from the other iterative steps in identifying the hierarchy levels within Table A1.

Step 5 involves developing the interpretive model that visualizes the organization of functions. Visualizing this model entails positioning the functions in their respective placement level according to their hierarchy level identified in Table A1, removing the transitivities, and depicting the direct relationships between functions of consecutive placement levels with vector arrows. Fig. 5 represents the interpretive model of the study. This model consists of seven placement levels, which reflects the seven extraction iterations identified across Table A1. Notably, the extraction sequence is the opposite of positioning order for the placement levels. For example, VNI extracted in the seventh iteration in Table A1 is positioned in placement level 1 in Fig. 5.

The final step in ISM is MICMAC analysis, the results of which have been presented in Fig. 6. MICMAC involves putting the functions into their respective quadrants according to their driving and dependence power. The driver functions, including VNI, SBI, STG, SKD, and WES, which have higher driving power but low dependence power, are clustered under the driver quadrant. The autonomous quadrant includes functions that are somewhat independent of other functions, recognized by low driving and dependence power. Therefore, MAP, MCR, and MRS are clustered under the autonomous quadrant. The linkage quadrant should include functions with high driving and dependence power. Fig. 6 reveals that none of the functions can be clustered under the linkage quadrant. Linkage variables are unstable, indicating the possibility of feedback loops among the system components. Ideally, no function should be clustered under the linkage quadrant, a condition that holds in this study. Finally, MPD, RIT, SEP, and MNR, which have low driving power but high dependence power, are clustered under the dependence quadrant. Achieving these functions is difficult since they

Table 2
The IRM.

Functions		*j*											
		MAP	MCR	MPD	MNR	MRS	RIT	SBI	SEP	SKD	STG	VNI	WES
i	MAP	1	0	1	0	1	0	0	0	0	0	0	0
	MCR	0	1	1	1	0	1	0	0	0	0	0	0
	MPD	0	0	1	1	0	0	0	1	0	0	0	0
	MNR	0	0	0	1	0	0	0	0	0	0	0	0
	MRS	0	0	0	1	1	0	0	0	0	0	0	0
	RIT	0	0	0	1	0	1	0	0	0	0	0	0
	SBI	0	1	1	0	0	1	1	1	0	1	0	1
	SEP	0	0	0	1	0	0	0	1	0	0	0	0
	SKD	0	1	0	0	0	1	0	1	1	0	0	1
	STG	0	1	0	0	0	1	1	1	0	1	0	1
	VNI	0	1	0	1	1	0	1	0	0	1	1	0
	WES	1	0	1	0	0	0	0	0	0	0	0	1

Table 3
The FRM.

Functions		*j*												
		MAP	MCR	MPD	MNR	MRS	RIT	SBI	SEP	SKD	STG	VNI	WES	*DRP*
i	MAP	1	0	1	1*	1	0	0	1*	0	0	0	0	***5***
	MCR	0	1	1	1	0	1	0	1*	0	0	0	0	***5***
	MPD	0	0	1	1	0	0	0	1	0	0	0	0	***3***
	MNR	0	0	0	1	0	0	0	0	0	0	0	0	***1***
	MRS	0	0	0	1	1	0	0	0	0	0	0	0	***2***
	RIT	0	0	0	1	0	1	0	0	0	0	0	0	***2***
	SBI	1*	1	1	1*	0	1	1	1	0	1	0	1	***9***
	SEP	0	0	0	1	0	0	0	1	0	0	0	0	***2***
	SKD	1*	1	1*	1*	0	1	0	1	1	0	0	1	***8***
	STG	1*	1	1*	1*	0	1	1	1	0	1	0	1	***9***
	VNI	0	1	1*	1	1	1*	1	1*	0	1	1	1*	***10***
	WES	1	0	1	1*	1*	0	0	1*	0	0	0	1	***6***
	DPP*	***5***	***5***	***8***	***12***	***4***	***6***	***3***	***9***	***1***	***3***	***1***	***5***	

Note: DRP, driving power; DPP, dependence power.

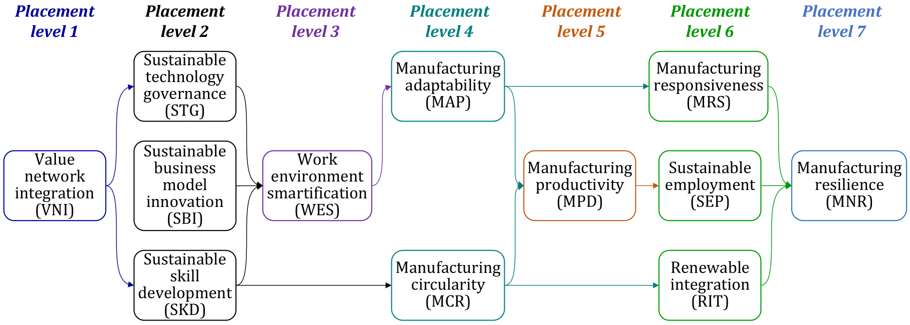


Fig. 5. The interpretive model of Industry 5.0-driven sustainable manufacturing.

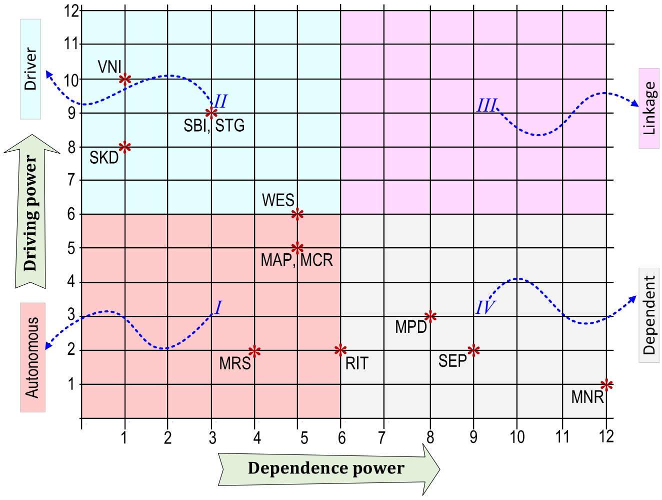


Fig. 6. MICMAC analysis.

depend on the achievement of preceding driver functions.

4.1. The strategic roadmap

Fig. 7 presents the roadmap to Industry 5.0-driven sustainable manufacturing. As we previously explained, a strategic roadmap should serve three functions. First, it should represent the actions and activities that satisfy the intended objectives of the technological transformation. Second, it should identify the sequence in which these actions and activities should be planned and organized. Third, it should identify and explain the functionality of their interactions while serving the transformation purpose. The roadmap in Fig. 7 draws on the results of the content-centric literature review and MICMAC analysis to list the functions through which Industry 5.0 may contribute to sustainable manufacturing and identify their role as a driver, autonomous, or dependent. Fig. 7 builds on the ISM results to determine the order in which the sustainable manufacturing functions of Industry 5.0 should be leveraged. It further draws on ISM outcomes to determine the precedence relationships among the functions. Finally, the roadmap draws on the ILB matrix presented in Table 4 to describe the implication of each contextual relationship between the functions. Therefore, the pairwise relationships identified in Fig. 7 should be interpreted by referring to Table 4. For example, referring to Table 4, the VNI→MNR relationship in Fig. 7 implies that the value network integration function of Industry 5.0 boosts public-private partnerships and streamlines manufacturing value chain coordination for better disruption management. It further improves the visibility of the supply networks and allows the rapid adjustments of production and supply systems to the unprecedented changes in the market, leading to higher responsiveness of manufacturers. The implications of the results are discussed in the following section.

5. Discussion

The study aimed to explain how the Industry 5.0 agenda and its underlying technologies and principles promote sustainable manufacturing. For this purpose, the study first conducted a comprehensive content-centric literature review, introduced the Industry 5.0 reference architecture, and identified 12 sustainable manufacturing functions of Industry 5.0. Further, the study drew on the ISM and ILB results and developed a strategic roadmap that explains how Industry 5.0 should be leveraged by its stakeholders to promote inclusive and sustainable manufacturing.

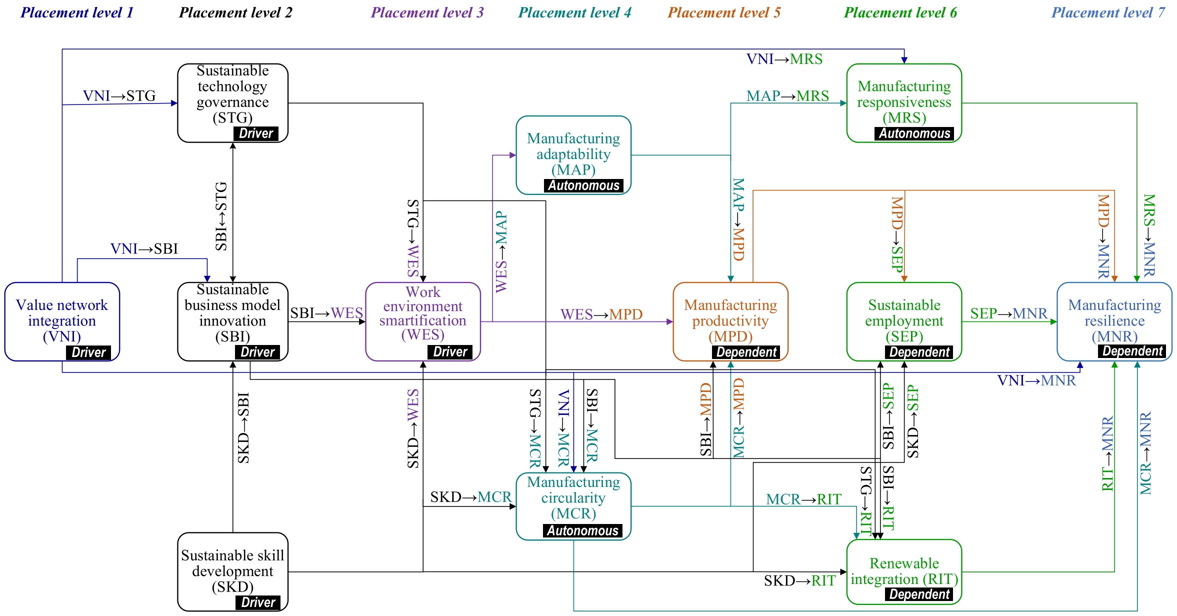


Fig. 7. The strategic roadmap for promoting sustainable manufacturing via Industry 5.0.

Overall, the roadmap implies that value network integration (VNI) is the most fundamental and driver function of Industry 5.0 for sustainable manufacturing. Industry 5.0 relies on its hallmark design principles, such as vertical integration, horizontal integration, real-time capability, and interoperability, to create a hyper-connected business environment where value partners can integrate their internal processes and operations. Therefore, VNI allows manufacturers to internally integrate core and support functions and externally integrate all their external stakeholders. Indeed, Industry 5.0 differentiates itself from Industry 4.0 by expanding the scope of VNI to the stakeholders. VNI is crucial for sustainable manufacturing, as it improves transparency, reduces waste, and prevents the risk of supply chain disruption. This finding supports Hao et al. (2018), who argued that a digitally enabled integrated manufacturing system is necessary for developing business practices that support sustainable development. The roadmap explains that VNI is essential to many other functions, including sustainable technology governance (STG) and sustainable business model innovation (SBI). The ILB in Table 4 explains that the enabling role of VNI for STG and SBI involves, among others, improved stakeholder involvement in the dynamics of technology governance and better identification of strategic intervention points where innovation can positively affect stakeholder and corporate dynamics.

STG, SBI, and sustainable skill development (SKD), positioned at the second placement level of the strategic roadmap, are other fundamental driver functions. Industry 5.0 delivers the STG function in two ways. First, Industry 5.0 is a stakeholder-centered agenda, offering a holistic approach to promote collaboration among technology stakeholders such as developers, civil society, and policymakers. Second, Industry 5.0 fosters sustainable innovation and creativity across the hyper-connected business environment, promoting ethical considerations across the technology development life-cycle. Alternatively, and to deliver the SBI function, Industry 5.0 draws on its core technologies, principles, and components to radically innovate various blocks of the business model. For example, the intelligent and connected product component will innovate and redefine manufacturers' value proposition, customer integration, and customer relationship management. This observation aligns with comparable studies (e.g., Ching et al., 2022), observing a similar link between Industry 4.0 constituents and green innovation capabilities. To deliver the SKD function, Industry 5.0 draws on its technical assistance principle and smart workplace technologies to promote upskilling and reskilling needed by industrial transformation. Industry 5.0 further facilitates skill development relevant to sustainability since boosting socio-environmental values is among the fundamental objectives of this agenda. In turn, STG, SBI, and SKD enable the work environment smartification (WES) function of Industry 5.0. WES entails the human-centric implications of smart workplace technologies such as CAI, smart wearables, and adaptive robots to improve working conditions, allowing employees to work more efficiently, productively, and conveniently. The roadmap implies that the direct enabling role of STG for WES entails applying holistic and socially responsible approaches to design and implement smart workplace technologies. This finding supports Ghobakhloo et al.'s (2023a) recent work highlighting the critical role of sustainable technology governance in the Industry 5.0 environment. SBI facilitates WES by empowering manufacturers to (1) mobilize and allocate resources needed for developing smart work environments and (2) restructure human resource strategies to facilitate the requirement of WES, including trust-based culture, team identity, and performance-driven contribution recognition. SKD enables WES by empowering employees to understand smart technologies' functions, integrate them into their daily activities, and manage possible side effects such as anxiety.

Placement level 4 in the strategic roadmap is inhabited by two autonomous functions, manufacturing strategic adaptability (MAP) and manufacturing circularity (MCR). Industry 5.0 delivers the MAP function by boosting manufacturers' analytical and intelligence capabilities and permeating the culture of learning and development across all business functions. Alternatively, Industry 5.0 draws on the integration design principle to deliver MCR via streamlining life-cycle performance management, building closed-loop systems, and ensuring traceability and transparency across the value network. Fig. 7 and Table 4 explain how the driver functions enable MAP and MCR. For example, WES directly enables MAP by increasing the accuracy of production decisions, the flexibility of manufacturing systems, and streamlining changeovers. This finding aligns with Leng et al. (2022) and Lu et al. (2022), who emphasized the critical role of human-machine symbiosis and smartification of the human workforce for Industry 5.0 sustainability values. Alternatively, SKD directly facilitates MCR by addressing the skill-intensity of remanufacturing tasks and implementing circular manufacturing practices. Manufacturing responsiveness (MRS) is another autonomous sustainable manufacturing function of Industry

Table 4
The ILB matrix for Industry 5.0 sustainable manufacturing functions.

Contextual relationship	Enabling role
Value network integration (VNI)	
VNI→MCR	Improved collaboration with product's life-cycle stakeholders; better insight into the end-of-life of the products; improved customer involvement in the circular economy loop
VNI→MNR	Improved public-private partnership and streamlined manufacturing value chain coordination for better disruption management; improved visibility to the supply networks and rapid adjustments of production and supply systems to the unprecedented changes in the market.
VNI→MRS	Removal of operational silos; more transparent and optimized inter and intra-organizational communication; better insights into market trends and improved forecasting for possible demand scenarios.
VNI→SBI	Streamlined mapping of the entire stakeholder ecosystem to identify environmental and societal issues associated with the existing business model; Better identification of strategic intervention points where innovation can positively affect stakeholder and corporate dynamics.
VNI→STG	Better stakeholder involvement in the dynamics of technology governance, from innovation design to performance measurement; minimization of Collingridge effect via (close to) real-time insights into the disruptive impact of new technological innovations.
Sustainable technology governance (STG)	
STG→MCR	Cleaner process technologies; improved intelligent design of new products aligned with sustainability goals; new technological solutions for boosting the efficiency of recycling and reusing.
STG→RIT	Development, integration, and operation of enabling technologies such as smart grids or supply-demand forecasting systems; prioritization of process technologies that support the integration of renewables and their underlying systems.
STG→SBI	Integration of cleaner and human-centric technologies into manufacturing processes; development of smarter and green products that expand the socio-environmental values of products.
STG→SEP	Structural shift in the strategic management of technological innovation and transitioning from technology-centricity to human-centric technological transitions.
STG→WES	Development and implementation of smart workplace technologies that allow employees to work smarter, improve the quality of the work environment, and enhance work-life balance.
Sustainable business model innovation (SBI)	
SBI→MCR	Restructuring of the 'key resources' block of the business model to redesign material selection and sourcing that boost re-utilization or recycling; Servitization and implementation of service-oriented business models that extend the product's end of first life.
SBI→MPD	Resource efficiency, improved throughput, and system reliability due to the process innovation; optimization of workforce efficiency; restructuring and streamlining products; integration of continuous improvement and waste aversion initiatives into the manufacturing operations.
SBI→RIT	Strategic prioritization of renewable integration across the manufacturing supply network; Improved capabilities for managing the volatility and risks of renewable integration.
SBI→SEP	Restructuring of human resource functional strategies to transition from displacement to upskilling and reskilling for employee retainment.
SBI→STG	Integration of technology accountability mechanisms into the business model; facilitating public engagement in the development and/or implementation of technological innovation via readjusting the partnership and relationship blocks of the business model. Integration of self-regulation mechanism into the research and development processes.
SBI→WES	Mobilization and allocation of resources needed for creating smart work environments to cover upfront investments and indirect maintenance and cybersecurity costs; restructuring of human resource strategies to facilitate the requirement of work environment smartification such as trust-based culture, team identity, and performance-driven contribution recognition.
Sustainable skill development (SKD)	
SKD→MCR	Upskilling and reskilling of the human workforce for the knowledge-intensive remanufacturing tasks; development of knowledge and competencies needed for restructuring business processes and implementing circular practices.
SKD→RIT	Addressing the blue/white-collar labor requirements of renewable system development, integration, and operation, from energy engineering and physical installation of renewable systems to energy analytics.
SKD→SEP	Enhancing employees' expertise and knowledge competencies and empowering them to adjust to changes in the work environment pushed by technologies; improved management competency for the sustainable management of human resources.
SKD→WES	Boosting employees' competencies to integrate innovative working technologies into their daily activities; enhancing employees' understanding of the smart technologies' function and purpose to alleviate potential anxiety and potential mistrust associated with the implementation process.
Work environment smartification (WES)	
WES→MAP	Faster and more effective changeovers; flexibility of manufacturing systems via the automation of routine manufacturing processes such as material handling; reduction of decision-making errors and mistakes; more adaptable teams due to information-driven learning and cross-training.
WES→MPD	Productivity of human resources; improved coordination among people and processes; more efficient decision and problem-solving processes.
Manufacturing adaptability (MAP)	
MAP→MPD	Improved production system reliability under the market variability and production customization scenarios; Reduction of lead time; product quality improvement and stability; downtime minimization.
MAP→MRS	Reconfigurability of resources, processes, and capabilities; Flexibility and scalability of manufacturing systems for supporting new functionalities.
Manufacturing circularity (MCR)	
MCR→MPD	Reduction of waste and emission; resource and energy efficiency
MCR→MNR	Improved resource life-cycle and alleviating the negative disruptive effect of raising manufacturing costs; reduced resource dependency and risk of material shortage thanks to the reuse and recycling principles.
MCR→RIT	Alleviating adverse environmental aspects of renewable implementation via recycling of rare earth elements such as lithium or prolonging the life-cycle of renewable energy systems; boosting manufacturers' ability to invest in renewables via reducing the manufacturing costs.
Manufacturing productivity (MPD)	
MPD→MNR	Improved economic resilience of manufacturers via enhanced revenue and profit margin due to the resource efficiency of circular activities, reduced operational costs; improved recoverability from disruptions.
MPD→SEP	Firm's ability to exploit the resulting revenue and profitability improvement to provide existing employees with engaging employment for extended working life; affording the employment of sustainability talents thanks to the improved resource availability.
Sustainable employment (SEP)	
SEP→MNR	Skills, competencies, and commitment needed for implementing service-based products, managing organizational changes pushed by disruptions, and new work responsibilities created by emerging realities of the business environment.
Manufacturing responsiveness (MRS)	
MRS→MNR	Quick response and adoption to the changing market and business circumstances; the scalability of production capability and order delivery; order fulfillment accuracy during disruptions.
Renewable integration (RIT)	
RIT→MNR	Reduced dependency on the global energy supply chains; improved compliance with the emerging sustainability demands in the market; improved business continuity via higher affinity between the public and manufacturers; risk mitigation concerning changes in the regulations or fluctuating price of fossil fuels.

5.0. MRS has been positioned in placement level 6 of the roadmap due to its weak driving power. The roadmap identifies VNI and MAP as the only enablers of MRS. Their enabling role for MRS involves eliminating operational silos, improving market forecasting, and increasing the reconfigurability of resources, capabilities, and production systems.

The dependent sustainable manufacturing functions of Industry 5.0 occupy placement levels 5, 6, and 7 in the strategic roadmap. The manufacturing productivity (MPD) function, positioned in the placement level 5 of the roadmap, reflects the sheer opportunities that Industry 5.0 technologies and principles may offer for addressing productivity gaps in the manufacturing context. However, MPD is a dependent function, meaning its materialization relies on the preceding driver and autonomous functions to deliver their intended values. For example, MAP and MCR boost MPD by increasing production reliability, product quality, and resource efficiency. Sustainable employment (SEP), renewable integration (RIT), and manufacturing resilience (MNR) are the most dependent functions that Industry 5.0 offers. These observations complement and extend the study of Ching et al. (2022) on the enabling role of Industry 4.0 for sustainable manufacturing, implying that Industry 5.0 offers a more complex mechanism for enabling sustainable manufacturing by providing unique and complex functions such as RIT and MNR that are not found within the Industry 4.0 environment.

While Industry 5.0 offers invaluable opportunities for sustainable manufacturing via these functions, the SEP, RIT, and MNR functions of Industry 5.0 cannot be fully capitalized on without leveraging the preceding driver and autonomous functions. For example, Fig. 7 and Table 4 imply that, among other functions, MPD facilitates SEP by boosting manufacturers' profitability and allowing them to provide engaging employment for extended working life and further employ sustainability talents. The roadmap also implies that to enable RIT, manufacturers should first leverage the MCR, SBI, SKD, and STG functions to strategically prioritize renewables integration, develop process technologies that support such integration level, and address the underlying skill requirements of renewable integration. MNR is arguably the most hard-to-leverage function of Industry 5.0 for sustainable manufacturing. MNR implies that Industry 5.0 can allow manufacturers to react to disorders promptly and recover from disruptions by boosting their agility and increasing the visibility and reliability of their supply chain operations. Nonetheless, this functionality also synergistically depends on other functions such as VNI, SEP, RIT, or MCR. For example, RIT allows manufacturers to become even more resilient to disruption as it reduces dependence on global energy supply chains, enhances compliance with the emerging sustainability demand, and mitigates risks associated with changes in the fuel price or energy consumption regulations.

6. Concluding remarks

Leading policy-making and academic institutions such as the European Union debate that technological advancement is unstoppable, yet social and ecological needs must be integrated into the ongoing techno-industrial revolution. It is why the Industry 5.0 concept has been progressively introduced to address the prevailing sustainability concerns associated with the concurrent industrial transformation. In this vein, the study strived to explain how the Industry 5.0 agenda can potentially boost sustainable manufacturing. The methodology applied and the resulting strategic roadmap is believed to offer considerable implications for research and practice.

6.1. Implications

Results indicate that Industry 5.0 can promote sustainable manufacturing through 12 functions. Industry 5.0 draws on its unique constituents (technologies, principles, and components) to deliver these functions. For example, the VNI function builds on vertical integration, horizontal integration, and interoperability design principles of Industry 5.0 to seamlessly integrate value network members' information and operations technologies. Each of the 12 functions identified provides fragmentary yet valuable opportunities for sustainable manufacturing. For instance, SEP primarily addresses job displacement and unemployment concerns of digital industrial transformation, whereas WES promotes the human-centricity aspect of sustainable manufacturing. This observation implies that each of the functions identified is uniquely consequential to promoting inclusive sustainable manufacturing under the Industry 5.0 agenda. It is imperative to highlight that many of the sustainable manufacturing functions specified in this study are not unique to Industry 5.0. For example, RIT has long been acknowledged as an essential enabler of sustainable industrial transformation. Nonetheless, Industry 5.0, by definition, seeks to build a technology and stakeholder-driven collaboration environment where value network partners, in particular manufacturers, are empowered to capitalize on all the 12 functions collectively and leverage their synergistic effects to promote inclusive sustainable manufacturing.

Overall, the results provide several practical and policy implications. First, Industry 5.0 stakeholders should integrate emerging technologies to prioritize the development of hyper-connected business environments that support the seamless integration of processes, operations, and human workforce. Such integration is critical to boosting transparency and risk mitigation in manufacturing supply networks, conditions essential to resilience and human-centricity objectives of Industry 5.0. Policymakers and industry leaders should support initiatives that promote collaboration and information sharing among Industry 5.0 stakeholders to streamline such integration.

Furthermore, policy actors are advised to foster collaboration among Industry 5.0 stakeholders, including manufacturers, technology developers, civic society, and legislators, to ensure a holistic approach to sustainable innovation. Therefore, developing and implementing governance frameworks that emphasize ethical considerations throughout the technology development life-cycle is essential. Similarly, policymakers are advised to boost manufacturers' capacity to implement sustainable business models by providing R&D development funding, supportive legislation, and collaboration platforms connecting academia and industry.

Manufacturers should note that digital transformation under Industry 5.0 is knowledge-intensive, requiring upskilling and reskilling programs that support human-machine symbiosis. Under such circumstances, smart workplace technologies can play a critical role in promoting skill development needed by the sustainability objectives of Industry 5.0. Stakeholders should collaborate on recognizing skills related to sustainable industrial transformation and providing funding for training to address the skill requirements of Industry 5.0 within the sustainable manufacturing context.

While acknowledging the complementarity of the 12 functions in boosting sustainable manufacturing, the strategic roadmap reveals that intricate precedence relationships exist among the functions. Indeed, Industry 5.0 stakeholders should leverage these functions in a specific order to maximize their synergistic implications for sustainable manufacturing. For instance, the roadmap explains that VNI and SKD are the primary and fundamental sustainable manufacturing functions of Industry 5.0 that should take priority since they are independent of other functions while playing a crucial enabling role for STG, SBI, and many other functions. Another important implication of the strategic roadmap concerns explaining each contextual relationship among the sustainable manufacturing functions, enabling Industry 5.0 stakeholders to interpret their interdependencies. For instance, the roadmap highlights that the sustainable technology governance function of Industry 5.0 accelerates a structural shift in the strategic management of technological innovation, empowering manufacturers to move toward sustainable employment by transitioning from technology-centricity to human-centric technological transitions.

While the European Commission has demonstrated a particular interest in the agenda, it is crucial to recognize that Industry 5.0 and its implications will extend far beyond Europe's context. Industry 4.0, the precursor to Industry 5.0, originated in Europe but quickly gained global recognition. Indeed, some of the most recognizable contributions to Industry 4.0 came from developed and emerging economies outside Europe, like the US, Australia, Brazil, and China. Industry 5.0 is expected to have a similar trajectory, with its transformative potential extending worldwide. Industry 5.0 has the potential to revolutionize manufacturing on a global scale. Hence, while the present work addressed European experts and their perspectives, the implications discussed are relevant and applicable to developed and transitioning economies worldwide. Indeed, transitioning and developing economies can profit from the lessons learned and best practices established by early adopters of the Industry 5.0 agenda, continuing to push the boundaries of innovation while promoting sustainable manufacturing practices. It is also believed that through collective global effort and collaboration, Industry 5.0 may deliver its transformative potential, reshaping the future of manufacturing across regions and contributing to a more inclusively sustainable global economy.

6.2. Limitations and future research

The study outlines a hypothetical best-case scenario where the Industry 5.0 agenda can inclusively promote sustainable manufacturing when the stakeholders manage, steer, and execute this agenda appropriately. Although Industry 5.0 is being pushed unprecedently, this agenda is in its infancy, and the mechanisms through which the enabling technologies can promote human and socio-centricity are empirically ill-defined. Emerging technologies such as generative AI or cognitive computing can be a double-edged sword for social values. For instance, AI appears to move toward automating human-occupied professions that are extraordinarily difficult to automate, as recently seen in the case of ChatGPT. Thus, a question remains who will ensure human centricity under Industry 5.0, and what legislative framework should be developed for such purposes? Addressing these questions opens an exciting and vital avenue for future research.

The archetype developed holds a stakeholder perspective in defining the scope of Industry 5.0 impacts. However, the archetype mainly exemplified the implications of Industry 5.0 transformation for manufacturing value networks, emphasizing the central role of adaptive smart factories. Like Industry 4.0, the ripple effects of Industry 5.0 will reach beyond the manufacturing industry, impacting other business sectors such as healthcare, transportation, construction, or energy. Future research is encouraged to expand the proposed archetype to the industry-specific roadmaps of Industry 5.0 transformation, identifying enabling technologies, principles, values, and components unique to each industry.

The study drew on the insights and perspectives of European experts to develop the strategic roadmap. Therefore, it is essential to exercise caution when generalizing the findings. Nonetheless, the identified functions and methodology employed in the present study can provide a foundation for future researchers to develop comparable strategic roadmaps and explore the implications of Industry 5.0 for sustainable manufacturing within diverse research and industrial contexts.

Finally, it is acknowledged that Industry 5.0 and its technological constituents (particularly AI) are dynamic and constantly evolving. The unprecedented emergence of new AI models like ChatGPT showed that emerging technologies could drastically and unexpectedly transform the business landscape positively or negatively. Shockingly, the disruption caused by these emerging technologies has not been limited to developed countries, having a global ripple effect. Because of the rapid pace of technological advancement, there is a pressing need for an inclusive measurement system to monitor and assess the sustainability performance of emerging technologies. Such a measurement system can empower Industry 5.0 stakeholders to govern better the integration of emerging technologies within the business and industrial settings to uphold societal values. Future studies are advised to prioritize research on developing and refining such a performance management system that can effectively capture the dynamics of Industry 5.0 technologies and their implications for sustainable manufacturing. This would enable stakeholders to navigate the complexities and dynamism of Industry 5.0 more effectively and ensure that its implementation aligns with broader sustainability goals.

CRediT authorship contribution statement

Morteza Ghobakhloo: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition, Supervision. **Mohammad Iranmanesh:** Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Behzad Foroughi:** Conceptualization, Writing – original draft, Writing – review & editing, Visualization. **Erfan Babaee Tirkolaee:** Writing – original draft, Software, Validation, Formal analysis. **Shahla Asadi:** Methodology, Software, Formal analysis, Data curation, Visualization. **Azlan Amran:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order to proofread some parts of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Table A1
The hierarchy level for Industry 5.0 sustainable manufacturing functions.

Function	Reachability set	Antecedent set	Intersection set	Extraction level
Iteration 1				
MAP	MAP, MPD, MNR, MRS, SEP	MAP, SBI, SKD, STG, WES	MAP	
MCR	MCR, MPD, MNR, RIT, SEP	MCR, SBI, SKD, STG, VNI	MCR	
MPD	MPD, MNR, SEP	MAP, MCR, MPD, SBI, SKD, STG, VNI, WES	MPD	
MNR	*MNR*	*MAP, MCR, MPD, MNR, MRS, RIT, SBI, SEP, SKD, STG, VNI, WES*	*MNR*	*I*
MRS	MNR, MRS	MAP, MRS, VNI, WES	MRS	
RIT	MNR, RIT	MCR, RIT, SBI, SKD, STG, VNI	RIT	
SBI	MAP, MCR, MPD, MNR, RIT, SBI, SEP, STG, WES	SBI, STG, VNI	SBI, STG	
SEP	MNR, SEP	MAP, MCR, MPD, SBI, SEP, SKD, STG, VNI, WES	SEP	
SKD	MAP, MCR, MPD, MNR, RIT, SEP, SKD, WES	SKD	SKD	
STG	MAP, MCR, MPD, MNR, RIT, SBI, SEP, STG, WES	SBI, STG, VNI	SBI, STG	
VNI	MCR, MPD, MNR, MRS, RIT, SBI, SEP, STG, VNI, WES	VNI	VNI	
WES	MAP, MPD, MNR, MRS, SEP, WES	SBI, SKD, STG, VNI, WES	WES	
Iteration 2				
MAP	MAP, MPD, MRS, SEP	MAP, SBI, SKD, STG, WES	MAP	

(*continued on next page*)

Table A1 (*continued*)

Function	Reachability set	Antecedent set	Intersection set	Extraction level
MCR	MCR, MPD, RIT, SEP	MCR, SBI, SKD, STG, VNI	MCR	
MPD	MPD, SEP	MAP, MCR, MPD, SBI, SKD, STG, VNI, WES	MPD	
MRS	*MRS*	*MAP, MRS, VNI, WES*	*MRS*	*II*
RIT	*RIT*	*MCR, RIT, SBI, SKD, STG, VNI*	*RIT*	*II*
SBI	MAP, MCR, MPD, RIT, SBI, SEP, STG, WES	SBI, STG, VNI	SBI, STG	
SEP	*SEP*	*MAP, MCR, MPD, SBI, SEP, SKD, STG, VNI, WES*	*SEP*	*II*
SKD	MAP, MCR, MPD, RIT, SEP, SKD, WES	SKD	SKD	
STG	MAP, MCR, MPD, RIT, SBI, SEP, STG, WES	SBI, STG, VNI	SBI, STG	
VNI	MCR, MPD, MRS, RIT, SBI, SEP, STG, VNI, WES	VNI	VNI	
WES	MAP, MPD, MRS, SEP, WES	SBI, SKD, STG, VNI, WES	WES	
Iteration 3				
MAP	MAP, MPD	MAP, SBI, SKD, STG, WES	MAP	
MCR	MCR, MPD	MCR, SBI, SKD, STG, VNI	MCR	
MPD	*MPD*	*MAP, MCR, MPD, SBI, SKD, STG, VNI, WES*	*MPD*	*III*
SBI	MAP, MCR, MPD, SBI, STG, WES	SBI, STG, VNI	SBI, STG	
SKD	MAP, MCR, MPD, SKD, WES	SKD	SKD	
STG	MAP, MCR, MPD, SBI, STG, WES	SBI, STG, VNI	SBI, STG	
VNI	MCR, MPD, SBI, STG, VNI, WES	VNI	VNI	
WES	MAP, MPD, WES	SBI, SKD, STG, VNI, WES	WES	
Iteration 4				
MAP	*MAP*	*MAP, SBI, SKD, STG, WES*	*MAP*	*IV*
MCR	*MCR*	*MCR, SBI, SKD, STG, VNI*	*MCR*	*IV*
SBI	MAP, MCR, SBI, STG, WES	SBI, STG, VNI	SBI, STG	
SKD	MAP, MCR, SKD, WES	SKD	SKD	
STG	MAP, MCR, SBI, STG, WES	SBI, STG, VNI	SBI, STG	
VNI	MCR, SBI, STG, VNI, WES	VNI	VNI	
WES	MAP, WES	SBI, SKD, STG, VNI, WES	WES	
Iteration 5				
SBI	SBI, STG, WES	SBI, STG, VNI	SBI, STG	
SKD	SKD, WES	SKD	SKD	
STG	SBI, STG, WES	SBI, STG, VNI	SBI, STG	
VNI	SBI, STG, VNI, WES	VNI	VNI	
WES	*WES*	*SBI, SKD, STG, VNI, WES*	*WES*	*V*
Iteration VI				
SBI	*SBI, STG*	*SBI, STG, VNI*	*SBI, STG*	*VI*
SKD	*SKD*	*SKD*	*SKD*	*VI*
STG	*SBI, STG*	*SBI, STG, VNI*	*SBI, STG*	*VI*
VNI	SBI, STG, VNI	VNI	VNI	
Iteration VII				
VNI	VNI	VNI	VNI	

Data availability

Data will be made available on request.

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