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Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values

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Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values

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ABSTRACT

Scholars believe that the newly introduced Industry 5.0 has the potential to move beyond the profit-centered productivity of Industry 4.0 and to promote sustainable development goals such as human-centricity, socio-environmental sustainability, and resilience. However, little has been done to understand how this ill-defined phenomenon may deliver its indented sustainability values despite these speculative promises. To address this knowledge gap, the present study developed a strategy roadmap that explains the mechanism by which Industry 5.0 delivers its intended sustainable development functions. The study first developed and introduced the Industry 5.0 reference model that describes the technical and functional properties of this phenomenon. The study further conducted a content-centric synthesis of the literature and identified the sustainable development functions of Industry 5.0. Next, the interpretive structural modeling (ISM) technique was employed to identify the sequential relationships among the functions and construct the Industry 5.0-enabled model of sustainable development. The ISM involved collecting the opinions of 11 Industry 5.0 experts through expert panel meetings. Results revealed that Industry 5.0 delivers sustainable development values through 16 functions. Circular intelligent products, employee technical assistance, intelligent automation, open sustainable innovation, renewable integration, and supply chain adaptability are examples of the functions identified. These functions are highly interrelated and should be developed in a specific order so that the synergies and complementarities among them would maximize the sustainable development value gains. The roadmap to Industry 5.0-driven sustainability developed in this study is expected to provide a better understanding of ways Industry 5.0 can contribute to sustainable development, explaining how the development of its functions should be managed to maximize their synergies and contribution to the intended sustainability values. The study also highlights important avenues for future research, emphasizing the potential enablers of Industry 5.0 development, such as Government 5.0 or Corporate Governance 5.0.

1. Introduction

The Industry 5.0 concept has recently emerged as the vision of a future industry that values protecting the environment and society. The advocates of Industry 5.0 believe that Industry 4.0 is not the proper framework for achieving sustainable development. The literature acknowledges that Industry 4.0 centers around technology-driven productivity (Ghobakhloo et al., 2021a). Although the internal productivity mechanism of Industry 4.0 inadvertently improves some micro-environmental sustainability metrics such as production efficiency or emission reduction (Ng et al., 2022), it cannot move past the profit-centricity of the contemporary production and consumption economic models (Sindhwani et al., 2022). Critiques argue that Industry 4.0 aligns with the long-lasting neoliberal capitalism models that emphasize profitability and shareholder primacy, intensifying some of the prevailing socio-environmental concerns such as regional inequality, environmental degradation,

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Nomenclature

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BPM	Business process monitoring
CADM	Computer-aided design and manufacturing
CAI	Cognitive artificial intelligence
CCPS	Cognitive cyber-physical systems
CIP	Circular intelligent products
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DST	Data sharing and transparency
ERP	Enterprise resource planning
ETA	Employee technical assistance
HIRT	Human interaction and recognition technologies
INA	Intelligent automation
ILB	Logic-knowledge base
IoE	Internet of everything
ISM	Interpretive structural modeling
MICMAC	Matrice d'Impacts Croisés Multiplication Appliqués à un Classement
ORE	Operational and resource efficiency
OSI	Open sustainable innovation
RIN	Renewable integration
RTC	Real-time communication
SCA	Supply chain adaptability
SCM	Supply chain modularity
SII	System integration and interoperability
SOP	Service-orientation and personalization
STH	Sustainable thinking
SUD	Sustainable development
UPR	Upskilling and reskilling
VUI	Value network integration

and fragility of the global economy (Grybauskas et al., 2022; Renda et al., 2022). Indeed, Industry 5.0 represents a transformative model that draws on the Industry 4.0 experience and Covid 19 disruptions to develop a hyperconnected and data-driven industrial ecosystem that values sustainable development goals (Javaid et al., 2020). Consistent with the European Commission's 2022 Industry 5.0 agenda, the sustainable development objectives of Industry 5.0 include the inclusive development of economic, environmental, and social pillars of sustainability and their underlying micro-objectives (Renda et al., 2022). In particular, this phenomenon aims to promote resilience, socio-environmental sustainability, and human-centricity under the sustainable development agenda (Saniuk et al., 2022). The human-centricity micro-objectives of Industry 5.0, for example, consist of employment growth, workplace dignity, employee autonomy, and job satisfaction (Breque et al., 2021). Despite these contributions, introducing Industry 5.0 as a new paradigm for achieving competitive sustainability is associated with two significant controversies. First, the boundaries, core principles, and functionality of Industry 5.0 are vastly understudied. Second, it is practically unclear how Industry 5.0 can contribute to promoting sustainable development. The present study strives to address these knowledge gaps.

Nowadays, some general agreements exist on the core values of Industry 5.0, at least on the three pillars of economic resilience, environmental sustainability, and human-centricity (Akundi et al., 2022). However, academic and industry experts offer diverse perspectives on the definition, functionality, and boundaries of this phenomenon. Scholars such as Longo et al. (2020) and Lu et al. (2022) believe that Industry 5.0 centers around human-centric manufacturing, and technological advancements should promote human well-being in social smart factories. Viewed from the environmental sustainability perspective, Sindhwani et al. (2022) explain that Industry 5.0 represents the vision of human-robot collaboration for a smart business ecosystem that promotes resource efficiency and bioeconomy. According to Sindhwani et al. (2022), the scope of Industry 5.0 expands beyond the manufacturing industry, involving other business sectors such as agriculture or healthcare. Alternatively, the European Commission builds on the Society 5.0 concept and considers Industry 5.0 a socio-economic structural shift toward a sustainable future industry. European Commission proposes that Industry 5.0 is not the chronological continuation of Industry 4.0. Instead, Industry 5.0 complements and, in many instances, extends its predecessor, adding socio-environmental dimensions to Industry 4.0 paradigm (Breque et al., 2021).

Besides the ambiguity surrounding the definition, functionality, and boundaries of Industry 5.0, the literature falls short in holistically explaining how this phenomenon can deliver its sustainable development values. Comparatively, Industry 4.0 is significantly well-studied, and the literature provides valuable insights into the underlying mechanism by which Industry 4.0 delivers its intended values, such as manufacturing productivity (Hughes et al., 2022), supply chain innovation (Hahn, 2020), sustainable manufacturing (Ng et al., 2022), or sustainable energy (Ghobakhloo and Fathi, 2021). Although scholars have recently made important contributions to understanding the values of Industry 5.0, these early contributions have addressed the micro implications of this phenomenon. For example, Sharma and Arya (2022) described how Industry 5.0 could improve smart city monitoring systems, whereas Fatima et al. (2022) showed how Industry 5.0 could lead to production and warehousing automation. Scholars argue that Industry 5.0 should equitably contribute to various aspects of sustainable development (Grabowska et al., 2022; Renda et al., 2022). Nonetheless, little has been done to understand how a transformative phenomenon such as Industry 5.0 and its underlying sustainability functions can interact with various micro and macro economic, environmental, and social sustainability objectives.

Referring to the knowledge gaps discussed above, the present study attempts to answer the following research questions:

RQ1. What are the underlying components and sustainability values of Industry 5.0?

RQ2. How can Industry 5.0 deliver sustainable development values?

To address the first research question, the study introduces the Industry 5.0 reference model that provides a description of this phenomenon, explaining its underlying technologies, techno-functional principles, smart components, and values. Concerning the second research question, the study conducts the content-centric synthesis of the literature and identifies the Industry 5.0 functions for sustainable development. The study further draws on ISM to explore how these functions should interact to deliver Industry 5.0 values such as resilience, socio-environmental sustainability, and human-centric operations. The resulting strategy roadmap for Industry 5.0-enabled sustainable transformation and the underlying findings are expected to offer notable implications for research and practice. Besides introducing the sustainable development functions of Industry 5.0, the study explains how their development should be managed so that the synergies resulting from precedence relationships and complementarity among the functions could maximize the intended sustainability values.

2. Literature review

This section describes the Industry 5.0 phenomenon and identifies the functions through which it might align with sustainable development, particularly in terms of resilience, sustainability, and human centricity.

2.1. Industry 5.0 definition and background

The Industry 5.0 concept has caused many controversies among academics and industrial communities. Researchers have offered various reasons for the prevalence of Industry 5.0. For example, Özdemir and Hekim (2018) defined Industry 5.0 as an evolutionary yet incremental upgrading of Industry 4.0 that can offer symmetrical innovation to address the limitations of the Industry 4.0 innovation ecosystem. Alternatively, scholars such as Nahavandi (2019) and Kumar et al. (2021) have criticized the productivity-centricity of Industry 4.0, proposing that Industry 5.0 denotes the emergence of human-centric industrial operations, pushed by a new wave of disruptive technologies that promote synergetic human-machine integration while improving working conditions, employment, and productivity. While providing diverse perspectives on this phenomenon, these early studies agreed on two fundamental features of Industry 5.0. First, early studies unanimously acknowledged that Industry 4.0 and the underlying industrial transformation had been associated with notable shortcomings such as the digital divide or technology-centricity (Longo et al., 2020). Indeed, recent studies, such as the work of Grybauskas et al. (2022), clearly outline such limitations or adverse sustainability impacts of Industry 4.0. Second, scholars widely believe that while Industry 5.0 builds on the technological constituents of Industry 4.0 (Xu et al., 2021), it associates with radical technological advancements in cognitive artificial intelligence (CAI), energy transitions technologies, and smart materials, to name a few (Maddikunta et al., 2022).

The development of the Industry 5.0 paradigm took a new turn when the European Commission released the perspective of Europe's technology leaders on Europe's future industry agenda under the label of Industry 5.0. While discussing the challenges of the term 'Industry 5.0,' this report proposed that "Industry 5.0 should not be understood as a replacement nor an alternative to, but an evolution and logical continuation of the existing Industry 4.0 paradigm" (Müller, 2020, p. 6). While acknowledging that Industry 5.0 is centered around human and ecological values, this report proposed that this phenomenon should ensure that novel technological innovation should be shaped toward supporting socio-environmental development (Müller, 2020). In 2021, European Commission released its Industry 5.0 agenda for resilient, sustainable, and humancentric European Industry. According to this agenda, Industry 5.0 is a complementary exercise, extending the Industry 4.0 paradigm to prioritize emerging socio-environmental needs (Breque et al., 2021). In early 2022, European Commission took a stronger position against Industry 4.0, arguing that this paradigm cannot be considered the proper framework for addressing the prevailing climate crisis and social tensions (Renda et al., 2022). This policy document proposes that Industry 5.0 represents a new vision for the industry, redefining the role and functionality of value chains, business models, and digital transformation in the hyperconnected business environment. According to this policy document (Renda et al., 2022) and very recent academic contributions (e.g., Grabowska et al., 2022; Maddikunta et al., 2022), Industry 5.0 differs from Industry 4.0 in the following manners:

- Industry 5.0 values both productivity-driven competitiveness and sustainable development;
- Industry 5.0 empowers the human workforce via promoting human-centric approaches to technological development;
- Industry 5.0 advances technological innovation (such as smart renewable systems) in the realm of environmental sustainability;
- Industry 5.0 promote stakeholder primacy in technology governance, innovation growth, and sustainability performance management;
- Industry 5.0 draws on certain technologies and functional principles to expand the scope of corporate responsibility to the entire value chain.

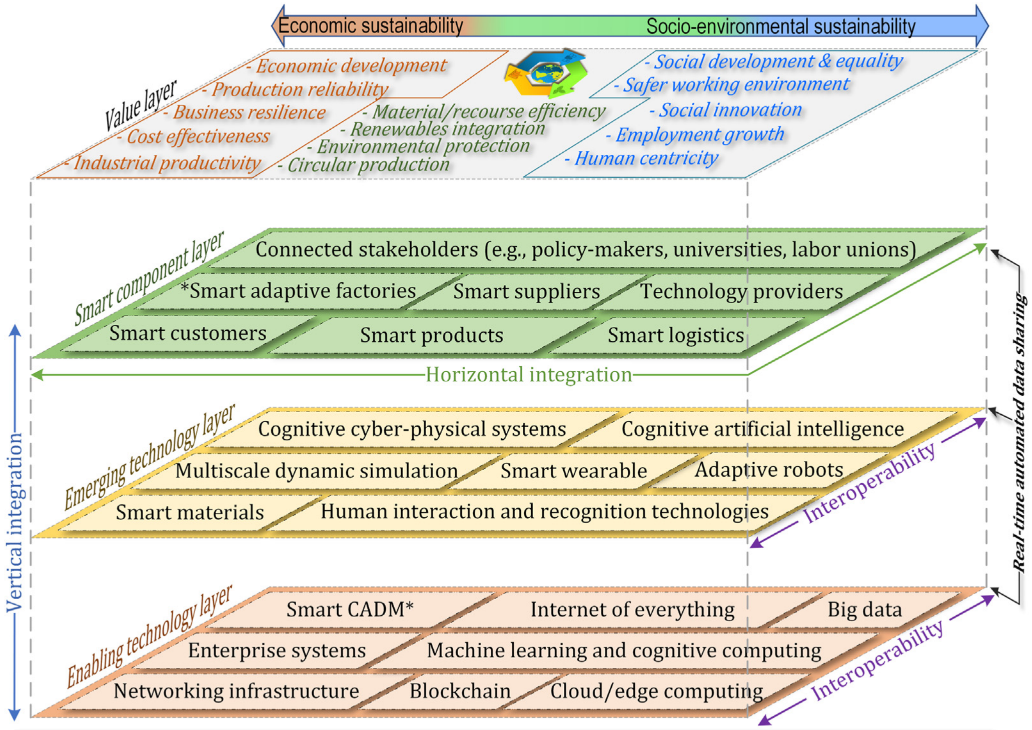
Nowadays, there is a general agreement that Industry 5.0 diverges from previous industrial revolutions as it represents a stakeholder-pulled socio-technological phenomenon that systematically shifts classic profit and consumption-driven economic models to circular, regenerative, sustainable, and resilient value-creating economic models.

2.2. Industry 5.0 reference model

Industry 5.0 is vastly understudied, and the early studies offer varying conceptualizations of this phenomenon and its underlying components. To address the ambiguity and complexity of this phenomenon, we develop and present the reference model of Industry 5.0 in Fig. 1. This reference model offers a holistic overview of this phenomenon, describing the technological constituents, principles, components, and core value objectives of Industry 5.0. Consistent with the European Commission agenda (Breque et al., 2021; Müller, 2020), we consider Industry 5.0 a socio-technological phenomenon. Industry 5.0 is a technological phenomenon, given that it centers around technological advancements and the digitalization of industrial value networks. Industry 5.0 is also a social phenomenon because it builds on the culture of social dialogue among stakeholders to manage and steer technological innovation to promote fundamental sociocultural values such as human dignity, equality, privacy, and autonomy (Renda et al., 2022).

Fig. 1 explains that the enabling technologies constitute the fundamental layer of the Industry 5.0 reference model. This layer consists of technologies that have emerged and matured since the third industrial revolution and have become commercially affordable and applicable since the emergence of Industry 4.0. Smart computer-aided design and manufacturing (CADM) tools (e.g., 3D printers), cloud computing, big data analytics, and enterprise systems are examples of the enabling technologies that deliver the primary production and efficiency growth objectives of digitalized business ecosystems under Industry 5.0 (Xu et al., 2021). The enabling technologies are also critical to the proper functioning of emerging technologies of Industry 5.0. For example, enterprise resource planning (ERP) is an indispensable enabling technology of Industry 5.0. ERP has its story started with the introduction of material resource planning more than half a century ago in the 1960s. ERP systems evolved to support manufacturing resource planning in the 1980s and became internet-enabled to support more complex functions such as human resource and customer relationship management in the early 2000s (Ghobakhloo et al., 2019). Modern ERPs integrate with cloud data, IoT, and artificial intelligence to provide real-time insights into various business and supply chain operations. Under Industry 5.0, smart ERPs are responsible for integrating with operations and information technologies such as process controllers, execution systems, or data abstraction tools to extract actionable business intelligence from raw data. ERP is essential to several micro-objectives of Industry 5.0, such as industrial productivity or product circularity (Wang et al., 2022).

Industry 5.0 also relies on the most disruptive technological innovations listed under the emerging technologies of the reference model to deliver its core objectives of human centricity, resilience, and sustainability (Müller, 2020). Fig. 1 shows that cognitive cyber-physical systems (CCPS), CAI, and smart wearables are among the emerging technologies of this phenomenon. Extant literature, such as the recent studies by Alvarez-Aros and Bernal-Torres (2021), Duggal et al. (2022), and Maddikunta et al. (2022), provide early insight into the properties of these technologies. For instance, CCPS involves integrating machine consciousness into CPS and operating on the novel sense-analyze-compute-act cycle (Alohali et al., 2022). The self-awareness and self-monitoring features of CCPS allow it to recognize the role of human cognition in offering safer and smoother man-machine symbiosis (John et al., 2021). To take a human-centric approach to the manufacturing environment, Industry 5.0 draws on adaptive robots, CCPS, and human interaction and recognition technologies to develop a human-centric solution that prioritizes core human worker needs while maintaining or improving industrial productivity (Maddikunta et al., 2022; Xu et al., 2021). For example, adaptive robots, complemented by edge computing, CAI, and cognitive computing, alleviate the limitation of traditional robots (restricted safety for human collaboration) and collaborative robots (limited load and speed) to offer high productivity while ensuring the safety and



Notes:
*CADM: Computer-aided design and manufacturing technologies such as 3D printers.
**Smart factories could be replaced with other smart entities depending on the industrial context. For example, smart hospitals would be a component of Industry 5.0 within the healthcare industry.

Fig. 1. The reference model of Industry 5.0.

convenience of the collaborating human operators (Lu et al., 2022). Recent advancements in smart wearable technologies also offer important implications for developing more human-centric industrial operations. For example, smart bio-inspired protective tools or head-worn intelligent wearables can significantly improve the information capacity, intelligence, stability, and productivity of the human workforce in industrial settings (Niknejad et al., 2020). Under Industry 5.0, smart wearables should integrate with CCPS, edge computing, and IoT to seamlessly communicate with various components of the smart working environment to function as intended (Duggal et al., 2022; Kubiak et al., 2022).

Concerning the resilience objective of Industry 5.0, businesses can draw on dynamic simulation, CAI, and big data to develop a digital replica of supply chain operations and identify bottlenecks, weak links, risks, and imminent disruptions to improve the adaptability and responsiveness of supply networks. Alternatively, modern supply chains can use the internet of everything (IoE), blockchain, smart materials, and smart CADM to increase operational agility and move toward new business models supporting product personalization and servitization (Frederico, 2021; Sindhwani et al., 2022).

The third layer of the reference model represents the essential components of this phenomenon. Like its predecessor, Industry 5.0 represents a paradigm shift entailing the digitalization of industrial value chains (Javaid et al., 2020; Rupa et al., 2021). Nevertheless, Industry 5.0 differs from Industry 4.0 as it holds the stakeholder perspective, taking a stakeholder-centered approach to defining the impact scope of this phenomenon and the expected value delivery mix (Madsen and Berg, 2021). Consistently, the smart component layer of the reference model consists of smart customers, suppliers, logistics, technology providers, and adaptive factories, which collectively create the hyperconnected and data-driven business ecosystem (Renda et al., 2022). More importantly, connected stakeholders such as policy-makers, universities, and labor unions are indispensable components of Industry 5.0. Integration of connected stakeholders is critical to Industry 5.0 because it is primarily a technology-driven phenomenon, and the majority of socio-environmental values cannot be delivered without systemic technology governance imposed by stakeholders to push its intended objectives (Saniuk et al., 2022). The European Commission even believes that Industry 5.0 requires Government 5.0 to respond to this phenomenon's policy, regulatory, funding, and innovation management needs (Renda et al., 2022). The reference model in Fig. 1 is primarily applicable to the manufacturing industry, yet its component can adjust to any industrial setting, given that the ripple effects of Industry 5.0 expand beyond the manufacturing sector. For example, Industry 5.0 would have important implications for the healthcare industry (Sharma et al., 2022), and the components can tailor to the particularities of this sector, for example, by adding smart hospitals and adjusting the smart adaptive factory component to the production of personalized healthcare products (Maddikunta et al., 2022).

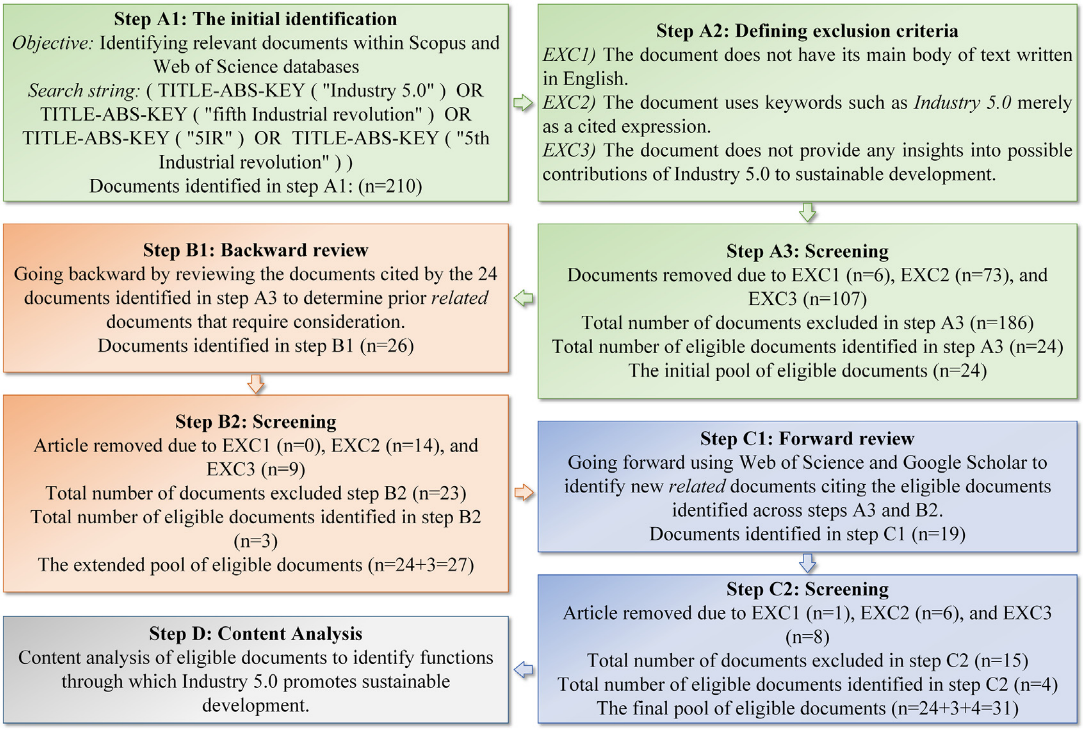
The double-headed arrow on the top of the value layer in the reference model proposes that Industry 5.0 is not merely economic-productivity driven as it systematically pursues balancing economic and socio-environmental sustainability. The Industry 5.0 reference model acknowledges that various aspects of economic, environmental, and social sustainability within the value layer are interrelated, and synergetic complementarity among them requires Industry 5.0 stakeholders to simultaneously pursue various sustainable development objectives. Business, supply chain, and economic resilience are the most emphasized economic sustainability objectives of Industry 5.0 (Akundi et al., 2022; Nahavandi, 2019). Under environmental sustainability, Industry 5.0's intended values involve preserving Earth's ecological and resource integrity via promoting the circular economy, carbon neutrality, renewable integration, and resource efficiency (Breque et al., 2021). Social sustainability values of Industry 5.0 involve promoting human-centric approaches to place fundamental human needs and rights at the heart of the industrial economy, promoting social development, employment, equality, and human agency (Carayannis and Morawska-Jancelewicz, 2022; Sindhwani et al., 2022).

Besides the enabling and emerging technologies, Industry 5.0 relies on certain techno-functional principles to deliver the intended digital transformation aspect of this phenomenon. These principles represent essential technical conditions that enable Industry 5.0 components, such as smart factories or customers, to leverage the underlying technologies and function properly according to this phenomenon's core objectives. As shown in the reference model, vertical integration, horizontal integration, interoperability, and real-time data sharing are among the fundamental techno-functional principles of Industry 5.0. When appropriately developed, techno-functional principles facilitate the development of the sustainable development functions of Industry 5.0, conditions that allow smart components efficiently leverage emerging and enabling technologies to deliver the sustainable development values of this phenomenon. For example, the real-time automated data sharing principle allows smart objects and modules of Industry 5.0 components to vertically or horizontally communicate in real-time when needed. This condition enables the real-time communication (RTC) sustainable development function of Industry 5.0 (Sharma et al., 2022). The RTC function allows real-time analysis and monitoring of supply chain nodes, providing real-time insight into supply chain operations and improving visibility and agility (Saniuk et al., 2022). The literature has diverse perspectives on this type of function. The study systematically reviews the literature to identify sustainable development functions of Industry 5.0, the results of which are reported in the following section.

3. Industry 5.0 sustainable development functions

The study conducted a content-centric synthesis of the literature to identify functions through which Industry 5.0 might promote sustainable development, especially in the three well-known goals of resilience, environmental sustainability, and human centricity. For this purpose, the research team followed the existing guides within the literature (e.g., Watson and Webster, 2020; Webster and Watson, 2002). Fig. 2 describes the steps undertaken to conduct the content-centric synthesis of the Industry 5.0 literature. Step A1, as explained in Fig. 2, involved conducting a systemic search of the Scopus and Web of Science, which identified 210 documents. In step A2, the research team defined three exclusion criteria to shortlist the most relevant documents. The 210 documents identified in step A1 were subjected to the exclusion criteria in step A3, leading to the initial pool of 24 eligible documents. The backward review was conducted across step B1, in which the reference section of the 24 eligible documents was analyzed to pinpoint potentially relevant documents not previously identified. This step led to identifying 26 new documents. These documents were subjected to the exclusion criteria in step B2. As a result, 23 documents were excluded, and three new eligible documents were shortlisted, leading to the extended pool of 27 (24 + 3) eligible documents. Step C1 involved conducting the forward review procedure, in which Google Scholar and the Web of Science platforms were used to review the title of documents that had cited the 27 eligible articles identified across steps A3 and B2. Throughout this step, the research team identified 19 new documents (not previously identified) that had important keywords such as Industry 5.0 or human-centricity explicitly mentioned within the title. In step C2, the exclusion criteria were applied to the newly identified 19 documents, excluding 15 documents and shortlisting four new eligible documents. Step C2 led to the final pool of 31 (24 + 3 + 4) eligible documents.

In step D, two research team members performed the conceptual content analysis of the eligible articles. Conceptual content analysis is the suitable synthesis technique in the present study, given that the main objective here is to identify, quantify, and count the occurrence of the terms of interest within the textual data (Krippendorff, 2018). The study developed and followed a detailed content analysis protocol to ensure the reliability and validity of the conceptual analysis findings. This protocol involved defining the necessary steps, such as the coding scheme of implicit terms, codification of text into controllable content categories, defining content assessment levels (e.g., themes vs. terms), coding systems of the concepts (e.g., existence vs. frequency), and denoising procedures for distinguishing concepts. Two content analysts independently conducted the conceptual content analysis while



Step A1: The initial 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"))
Documents identified in step A1: (n=210)

Step A2: Defining exclusion criteria
EXC1) The document does not have its main body of text written in English.
EXC2) The document uses keywords such as *Industry 5.0* merely as a cited expression.
EXC3) The document does not provide any insights into possible contributions of Industry 5.0 to sustainable development.

Step A3: Screening
Documents removed due to EXC1 (n=6), EXC2 (n=73), and EXC3 (n=107)
Total number of documents excluded in step A3 (n=186)
Total number of eligible documents identified in step A3 (n=24)
The initial pool of eligible documents (n=24)

Step B1: Backward review
Going backward by reviewing the documents cited by the 24 documents identified in step A3 to determine prior *related* documents that require consideration.
Documents identified in step B1 (n=26)

Step B2: Screening
Article removed due to EXC1 (n=0), EXC2 (n=14), and EXC3 (n=9)
Total number of documents excluded step B2 (n=23)
Total number of eligible documents identified in step B2 (n=3)
The extended pool of eligible documents (n=24+3=27)

Step C1: Forward review
Going forward using Web of Science and Google Scholar to identify new *related* documents citing the eligible documents identified across steps A3 and B2.
Documents identified in step C1 (n=19)

Step C2: Screening
Article removed due to EXC1 (n=1), EXC2 (n=6), and EXC3 (n=8)
Total number of documents excluded in step C2 (n=15)
Total number of eligible documents identified in step C2 (n=4)
The final pool of eligible documents (n=24+3+4=31)

Step D: Content Analysis
Content analysis of eligible documents to identify functions through which Industry 5.0 promotes sustainable development.

Fig. 2. The methodology applied for identifying the sustainable development functions of Industry 5.0.

adhering to the protocol to minimize the threat of assessor bias. After performing the content analysis independently, the two assessors shared their results and collaboratively performed the reexamination and reassessment of the text in the case of disagreements. Accordingly, the assessors collaboratively crosschecked their results, interpreted the conflicting findings, and reached a shared consensus on the functions through which Industry 5.0 might promote sustainable development, as perceived by the eligible documents. Step D led to identifying 16 functions of Industry 5.0 for promoting sustainable development, primarily in terms of resilience, sustainability, and human-centricity. Table 1 lists these functions and their acknowledgment strength within the eligible documents.

4. Methods

There are several well-established methods and techniques for dealing with complex decision problems and systems, examples of which include the Analytic Network Process (ANP), Analytic Hierarchy Process (AHP), ISM, and Decision-Making Trial and Evaluation Laboratory (DEMATEL). ISM was used as the most appropriate technique for addressing the objectives of this study. As with any decision modeling technique, ISM comes with advantages and limitations. Following, we explain our reasoning for using ISM in the present study and how we have dealt with the limitation of this technique. In general, ISM is associated with the following significant benefits (Sushil, 2012; Vimal et al., 2022):

- ISM can draw on qualitative data collection methods such as in-depth interviews or group decision-making techniques to capture the experts' collective opinion and knowledge base;
- ISM can systematically use conceptual, judgmental, and computational resources to provide an in-depth understanding of the pattern of contextual relations among elements of a complex system;
- ISM allows the interpretation of the contextual relationships among each pair of elements. ISM can also pair with an interpretive logic-knowledge base (built on experts' opinions) to interpret the functionality of each pair of relationships.

ISM allows scholars to draw on expert opinions and develop visual representations of poorly explored and complex systems. The present study is exploratory because Industry 5.0 is in its embryonic stage and significantly understudied. Thus, ISM is employed to explore the sustainable development functions of Industry 5.0 and structure them into a comprehensive interpretive model.

More importantly, the study aims to develop a strategy roadmap that identifies the interrelationships among Industry 5.0 sustainable development functions and describes the internal mechanism through which Industry 5.0 can deliver sustainability, resilience, and human-centricity based on the experts' collective opinion. The development of such a strategy roadmap has two requirements. The first requirement is to identify the precedence relationships among system elements, which is supported by most decision modeling techniques such as ISM, DEMATEL, and their fuzzy variants. The second requirement relates to expert-based group decision-making, where experts should engage in live discussions to produce a shared consensus regarding each pairwise relationship and its detailed functionality. To our knowledge, the original ISM offers the best compatibility of the two requirements of strategy roadmapping, as also highlighted by prior studies comparable to the present work, for example, to roadmap Industry 4.0 implications for sustainable innovation (Ghobakhloo et al., 2021a), energy sustainability (Ghobakhloo and Fathi, 2021), and sustainable manufacturing (Ng et al., 2022). ISM is prone to two major limitations when used for strategy roadmapping. The first limitation pertains to the experts' knowledge bias or unequal expert participation in collaborative decision-making. We have applied

Table 1
Sustainable development functions of Industry 5.0 and their acknowledgment within the literature.

Authors	BPM[a]	CIP	DST	ETA	INA	ORE	OSI	RIN	RTC	SCA	SCM	SII	SOP	STH	UPR	VUI
Özdemir and Hekim (2018)							x									
Demir and Cicibaş (2019)		x		x			x	x						x		
Demir et al. (2019)				x			x	x							x	
Haleem and Javaid (2019)			x		x								x			
Nahavandi (2019)	x			x	x	x								x		
Aslam et al. (2020)				x			x						x			
Gorodetsky et al. (2020)			x				x						x			
Javaid and Haleem (2020)		x			x		x			x			x		x	
Javaid et al. (2020)	x		x		x	x					x	x				x
Longo et al. (2020)		x	x											x	x	
Doyle Kent and Kopacek (2021)					x										x	
ElFar et al. (2021)		x					x	x						x		
Fraga-Lamas et al. (2021a)						x		x	x							x
Fraga-Lamas et al. (2021b)	x		x						x			x				
Johri et al. (2021)					x		x					x	x			
Kumar et al. (2021)		x	x		x	x						x				
Margherita and Braccini (2021)				x		x										
Mladineo et al. (2021)	x			x	x	x								x		
Thakur and Kumar Sehgal (2021)									x			x				
Xu et al., 2021		x	x	x		x				x		x			x	x
Akundi et al. (2022)	x			x	x	x		x			x				x	
Carayannis and Morawska-Jancelewicz (2022)							x							x	x	x
Dautaj and Rossi (2022)				x										x		
Fatima et al. (2022)	x		x		x	x	x			x	x					x
Gürdür Broo et al. (2022)															x	
Lu et al. (2022)	x			x	x	x			x						x	
Maddikunta et al. (2022)		x				x				x	x	x	x			x
Patera et al. (2022)		x							x			x				
Saniuk et al. (2022)						x			x	x		x	x	x		x
Sharma et al. (2022)		x				x	x		x			x	x			x
Sindhwani et al. (2022)		x		x			x	x					x			

[a] Note: BPM, business process monitoring; CIP, circular intelligent products; DST, data sharing and transparency; ETA, employee technical assistance; INA, intelligent automation; ORE, operational and resource efficiency; OSI, open sustainable innovation; RIN, renewable integration; RTC, real-time communication; SCA, supply chain adaptability; SCM, supply chain modularity; SII, system integration and interoperability; SOP, service-orientation and personalization; STH, sustainable thinking; UPR, upskilling and reskilling; VUI, value network integration.

rigorous measures to minimize such bias threats, such as moderating expert panel meetings in a structured manner or using a self-assessment questionnaire for identifying eligible experts. The second limitation relates to the ISM's weakness in interpreting the identified contextual relationships (Sushil, 2012). We have addressed this limitation by developing a knowledge base and recording experts' collective opinions concerning the functionality of each pairwise relationship identified. Fig. 3 describes the process of conducting ISM in the present study and its underlying steps, which follow the standard ISM methodology widely accepted within the literature (e.g., Huang et al., 2021).

4.1. Collecting expert opinion

ISM uses experts' opinions and insights to determine the contextual relationships among elements of a system. Accordingly, the present study collected the Industry 5.0 expert opinion to determine the relationships among the sustainable development functions of this phenomenon. The research team followed the widely acknowledged expert identification and selection guides (e.g., Hertzum, 2014) to develop and implement a reliable expert selection protocol. The research team mainly targeted European experts because of two reasons. First, Industry 5.0 and its predecessor primarily originate from Europe. Second, the present study was directly funded by a European Commission H2020 ERA Chair program, providing the necessary resources to contact and collaborate with top European Industry 5.0 expert group advising the Commission or other European policymaking bodies on how to devise forward-looking digital transformation policies for Europe's future industry.

Following the expert selection protocol, the research team collaborated with partners (e.g., academic, industry, or executive collaborators) and identified 24 experts potentially knowledgeable about and conversant with Industry 5.0. These experts were contacted and requested to fill in a simple self-assessment questionnaire measuring their familiarity with the Industry 5.0 phenomenon. The self-assessment questionnaire consisted of six open-ended questions (Please refer to Appendix A). Out of 24 experts contacted, 21 answered the self-assessment questionnaire. The research team collectively assessed the 21 self-assessment questionnaires returned, based on which 17 experts were identified as eligible to participate in the expert panel meetings. Out of the four experts identified as ineligible, one showed a lack of familiarity with the Industry 5.0 concept, one highlighted the lack of necessary English proficiency to engage in expert panel discussions effectively, and two declared an inability to commit to all expert panel meetings fully. After sending the invitations and follow-ups to the 17 eligible experts, 11 experts agreed to participate. Although ISM background does not provide any robust sample size rules, most studies agree on having 5 to 13 experts (e.g., Ng et al., 2022; Sarabi et al., 2020), mainly when using qualitative data collection methods like in-depth interviews or group brainstorming. Thus, the sample of 11 experts deems reliable in the present study.

The 11 experts consisted of four females and seven males, all academicians who had experienced collaborating with the European Commission as policy advisors, members/consultants of executive boards, or senior collaborators of the European Union's research and innovation funding programme in the areas of digitalization and sustainability. In terms of academic background, the expert team consists of two professors of sustainable development, a professor of complex systems and spatial planning, an associate professor of sustainability leadership, a professor of logistics and operations management, an associate professor of production engineering, senior research flow of innovation and digital economy, an associate professor of political science, a professor of digital technologies, an associate professor of applied computer science, and an associate professor of sustainable and secure digital transformation.

Experts' opinions and insights were collected across six online expert panel meetings organized via the nominal group technique. Using the nominal group technique-based expert panel meeting is a reliable and widely accepted method for capturing expert opinion within the ISM literature (Ghobakhloo et al., 2021a; Ng et al., 2022). Using nominal group technique for organizing expert panel meetings and capturing experts' opinions involved four standard septs: (1) clarification step explaining intended goals of each meeting, (2) expert silent ideation, (3) round-robin expert insight recording, and (4) collaborative opinion discussion. Using these standard steps, the experts evaluated, refined, and validated the 16 sustainable development functions of Industry 5.0 across the first two meetings. Overall, the experts acknowledged the categorization of functions yet recommended minor revisions to

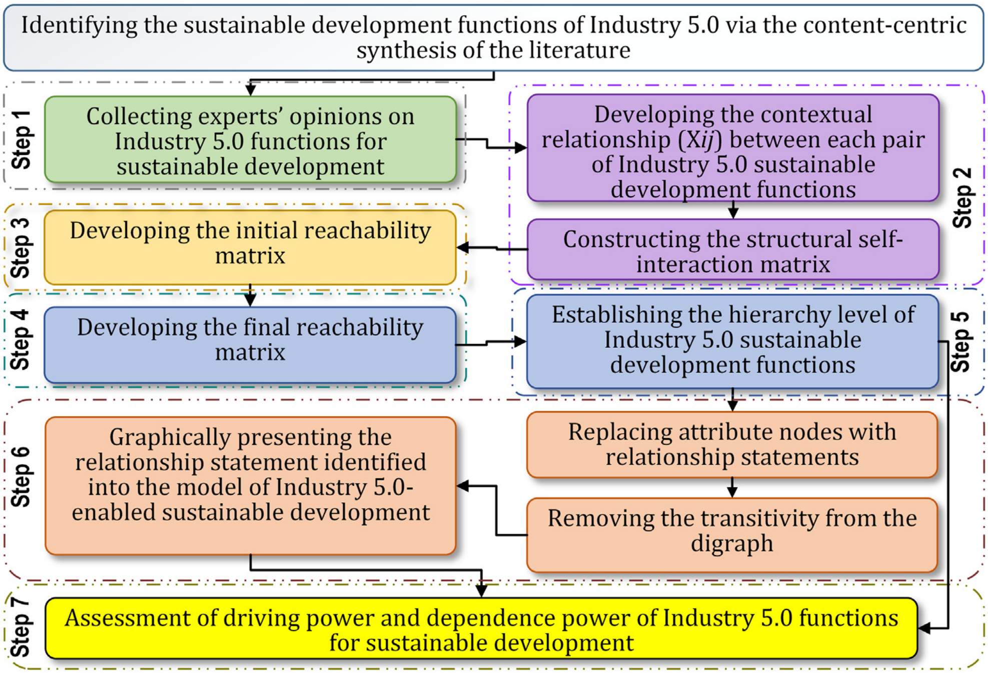


Fig. 3. The ISM methodology for the present study.

their titling. Experts collaboratively identified the contextual relationships among each pair of the sustainable development functions of Industry 5.0 across meetings 3 to 6. Besides the four standard steps, these meetings included three additional steps: (1) pilot voting on interrelationships among sustainable development functions, (2) discussing the preliminary relationships identified, and (3) final voting on the interrelationship between each pair of Industry 5.0 sustainable development functions. The research team followed the widely accepted guides to execute, moderate, and manage the meetings systematically to prevent bias and ensure the validity of outcomes.

4.2. Developing contextual relationships

This step involves using the following widely accepted coding system to identify the contextual relationships among system elements based on expert opinion and constructing the structural self-interaction matrix.

V: Sustainable development function *i* causes (determines) sustainable development function *j*;

A: Sustainable development function *i* is caused (determined) by sustainable development function *j*:

X: Sustainable development functions *i* and *j* mutually cause (determine) each other;

O: Sustainable development functions *i* and *j* are unrelated (independent).

Drawing on the expert opinions captured across expert panel meetings and building on the coding system explained above, the structural self-interaction matrix for the present study is developed and presented in Table 2. For example, the ETA-SII entry is symbolized as A in this table, meaning employee technical assistance (ETA) is determined by system integration and interoperability (SII).

4.3. Developing initial reachability matrix

Developing the initial reachability matrix entails subjecting the structural self-interaction matrix to the following transition coding scheme. Applying this coding system to the structural self-interaction matrix of the study, the initial reachability matrix is developed and presented in Table 3.

When the entry (*i*, *j*) in structural self-interaction matrix is symbolized by V, the entries (*i*, *j*) and (*j*, *i*) in initial reachability matrix are, respectively, set to 1 and 0;

When the entry (*i*, *j*) in structural self-interaction matrix is symbolized by A, the entries (*i*, *j*) and (*j*, *i*) in initial reachability matrix are, respectively, set to 0 and 1;

When the entry (*i*, *j*) in structural self-interaction matrix is symbolized by X, the entries (*i*, *j*) and (*j*, *i*) in initial reachability matrix are both set to 1;

When the entry (*i*, *j*) in structural self-interaction matrix is symbolized by O, the entries (*i*, *j*) and (*j*, *i*) in initial reachability matrix are both set to 0.

4.4. Developing final reachability matrix

This step involves developing the final reachability matrix by subjecting the relationships identified within the initial reachability matrix (Table 3) to the transitivity rule (Vimal et al., 2022). This rule implies that if element A causes element B and element B causes element C, then element A inadvertently causes element C, regardless of their relationships identified within the initial reachability matrix. Table 4 presents the final reachability matrix of the study. The '1*' values in Table 4 represent the application of the transitivity rule to individual relationships. The DST-INA value in Table 4, represented by 1*, can be exemplified to explain this rule better. The DST-INA entry in initial reachability matrix (Table 3) is 0, which means DST does not cause INA. However, DST directly causes VUI (DST-VUI entry in Table 3 is 1),

Table 2
The structural self-interaction matrix for Industry 5.0 sustainable development functions.

Functions		*j*															
		Value network integration (VUI)	Upskilling and reskilling (UPR)	Sustainable thinking (STH)	Service-orientation and personalization (SOP)	System integration and interoperability (SII)	Supply chain modularity (SCM)	Supply chain adaptability (SCA)	Real-time communication (RTC)	Renewable integration (RIN)	Open sustainable innovation (OSI)	Operational and resource efficiency (ORE)	Intelligent automation (INA)	Employee technical assistance (ETA)	Data sharing and transparency (DST)	Circular intelligent products (CIP)	Business process monitoring (BPM)
	BPM	A	O	O	O	A	A	V	A	O	O	V	A	A	A	V	–
	CIP	A	O	A	A	O	O	V	A	X	A	V	O	O	A	–	
	DST	X	V	V	O	A	O	V	A	V	V	O	A	V	–		
	ETA	O	A	V	O	A	O	O	A	O	A	V	A	–			
	INA	A	V	O	O	A	V	V	A	V	O	V	–				
	ORE	A	O	O	A	O	A	V	O	O	O	–					
	OSI	A	V	A	V	O	O	V	O	V	–						
i	RIN	A	O	A	O	A	O	O	A	–							
	RTC	A	O	O	V	A	O	V	–								
	SCA	O	O	O	A	A	A	–									
	SCM	O	O	O	V	A	–										
	SII	V	O	O	V	–											
	SOP	A	O	A	–												
	STH	O	V	–													
	UPR	O	–														
	VUI	–															

Table 3
The initial reachability matrix for Industry 5.0 sustainable development functions.

Functions	Business process monitoring (BPM)	Circular intelligent products (CIP)	Data sharing and transparency (DST)	Employee technical assistance (ETA)	Intelligent automation (INA)	Operational and resource efficiency (ORE)	Open sustainable innovation (OSI)	Renewable integration (RIN)	Real-time communication (RTC)	Supply chain adaptability (SCA)	Supply chain modularity (SCM)	System integration and interoperability (SII)	Service-orientation and personalization (SOP)	Sustainable thinking (STH)	Upskilling and reskilling (UPR)	Value network integration (VUI)
BPM	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0
CIP	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0
DST	1	1	1	1	0	0	1	1	0	1	0	0	0	1	1	1
ETA	1	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0
INA	1	0	1	1	1	1	0	1	0	1	1	0	0	0	1	0
ORE	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
OSI	0	1	0	1	0	0	1	1	0	1	0	0	1	0	1	0
RIN	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
RTC	1	1	1	1	1	0	0	1	1	1	0	0	1	0	0	0
SCA	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
SCM	1	0	0	0	0	1	0	0	0	1	1	0	1	0	0	0
SII	1	0	1	1	1	0	0	1	1	1	1	1	1	0	0	1
SOP	0	1	0	0	0	1	0	0	0	1	0	0	1	0	0	0
STH	0	1	0	0	0	0	1	1	0	0	0	0	1	1	1	0
UPR	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
VUI	1	1	1	0	1	1	1	1	1	0	0	0	1	0	0	1

and VUI directly causes INA (VUI-INA entry in Table 3 is 1). Therefore, according to the transitivity rule, DST is assumed to cause INA within the final reachability matrix. Table 4 also represents the driving power and dependence power of functions. The driving power value for a given function equals the number of functions it causes within the final reachability matrix, while the dependence power equals the number of functions caused by. The driving and dependence power values will be used in the MICMAC (Matrice d'Impacts Croisés Multiplication Appliqués à un Classement) analysis.

4.5. Establishing hierarchy level

As the most crucial outcome of ISM, the graphical interpretive model is developed by positioning system elements (functions in this study) into their appropriate placement levels. Identifying placement levels involves establishing the hierarchy level of Industry 5.0 sustainable development functions. This procedure entails using entry values in the final reachability matrix to develop the reachability, antecedent, and intersection sets for each sustainable development function. For a given function, the reachability set consists of the function itself and other functions caused by it, whereas the antecedent set comprises the function itself and other functions that determine it. The intersection set for the given function consists of functions shared across its reachability and antecedent sets (Ghobakhloo et al., 2021a).

Establishing hierarchy levels commences by building each function's reachability, antecedent, and intersection sets in iteration 1. Next, the extraction procedure takes place, in which function(s) with identical reachability and intersection sets are extracted (and removed) from the remaining sets in upcoming iterations. Table A1 represents the process of identifying the hierarchy level of Industry 5.0 sustainable development functions. Iteration 1 of this table identifies SCA for extraction because it is the only function with identical reachability and intersection sets. The extraction process in iteration 1 involves removing SCA from all remaining reachability, antecedent, and intersection sets. Accordingly, the iterative extraction process is continued iteratively until the hierarchy level of each sustainable development function is identified. Table A1 explains that the hierarchy levels of functions in the present study are established across ten iterations. Thus, the graphical interpretive model would consist of 10 placement levels.

4.6. Developing the interpretive model

This step involves positioning the sustainable development functions to their designated placement levels based on their extraction (hierarchy) level and representing the direct relationships between the functions with vector arrows. The interpretive model of Industry 5.0-enabled sustainable development is presented in Fig. 4. Consistent with the ten iterations of extractions in Table A1, the model positions the functions across ten placement levels. Nonetheless, the placement order in this model is the direct opposite of the extraction sequence identified in Table A1. This placement system follows the ISM literature recommending that function(s) with the highest driving power, extracted at the last iteration, should be placed at the beginning of the interpretive model due to their enabling role (e.g., Ghobakhloo and Fathi, 2021; Huang et al., 2021). According to the ISM methodology, the transitivity rule should be ignored while developing the interpretive model (Vimal et al., 2022). It means that vector arrows should only visualize the direct relationships between the functions across successive placement levels. SII → VUI, INA → SCM, and STH → RIN relationships are the exception in this model, extending the relationships over successive placement levels. For example, for the SII → VUI relationship, it is notable that no functions in placement level 2 determine VUI. Thus, the SII, positioned in placement level 1 (two levels lower), has been linked to VUI with the vector arrow. The same logic holds for INA → SCM and STH → RIN relationships.

Table 4
The final reachability matrix for Industry 5.0 sustainable development functions.

Functions	Business process monitoring (BPM)	Circular intelligent products (CIP)	Data sharing and transparency (DST)	Employee technical assistance (ETA)	Intelligent automation (INA)	Operational and resource efficiency (ORE)	Open sustainable innovation (OSI)	Renewable integration (RIN)	Real-time communication (RTC)	Supply chain adaptability (SCA)	Supply chain modularity (SCM)	System integration and interoperability (SII)	Service-orientation and personalization (SOP)	Sustainable thinking (STH)	Upskilling and reskilling (UPR)	Value network integration (VUI)	**Driving power**	*Rank*
BPM	1	1	0	0	0	1	0	1*	0	1	0	0	1*	0	0	0	**6**	*6*
CIP	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	**4**	*8*
DST	1	1	1	1	1*	1*	1	1	1*	1	0	0	1*	1	1	1	**14**	*3*
ETA	1	1*	0	1	0	1	1*	1*	0	1*	0	0	1*	1	1*	0	**10**	*4*
INA	1	1*	1	1	1	1	1*	1	0	1	1	0	1*	1*	1	1*	**14**	*3*
ORE	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	**2**	*9*
OSI	1*	1	0	1	0	1*	1	1	0	1	0	0	1	1*	1	0	**10**	*4*
RIN	0	1	0	0	0	1*	0	1	0	1*	0	0	1*	0	0	0	**5**	*7*
RTC	1	1	1	1	1	1*	1*	1	1	1	1*	0	1	1*	1*	1*	**15**	*2*
SCA	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	*10*
SCM	1	1*	0	0	0	1	0	0	0	1	1	0	1	0	0	0	**6**	*6*
SII	1	1*	1	1	1	1*	1*	1	1	1	1	1	1	1*	1*	1	**16**	*1*
SOP	0	1	0	0	0	1	0	1*	0	1	0	0	1	0	0	0	**5**	*7*
STH	0	1	0	1*	0	1*	1	1	0	1*	0	0	1	1	1	0	**9**	*5*
UPR	1*	0	0	1	0	1*	0	0	0	0	0	0	0	1*	1	0	**5**	*7*
VUI	1	1	1	1*	1	1	1	1	1	1*	1*	0	1	1*	1*	1	**15**	*2*
Dependence power	**10**	**13**	**5**	**9**	**5**	**15**	**8**	**12**	**4**	**15**	**5**	**1**	**12**	**9**	**9**	**5**		
Rank	*4*	*2*	*7*	*5*	*7*	*1*	*6*	*3*	*8*	*1*	*7*	*9*	*3*	*5*	*5*	*7*		

4.7. Driving and dependence analysis

MICMAC is a comparative classification and evaluation tool that draws on the driving power and dependence power values identified across the final reachability matrix (Table 4) to visualize and compare enabling role and dependability of functions. Fig. 5 presents the MICMAC analysis of the present study. MICMAC analysis entails classifying the functions into four quadrants: autonomous, linkage, driver, and dependent (Ng et al., 2022). The driver quadrant includes Industry 5.0 sustainable development functions with strong driving and weak dependence power. The driver functions are SII, RTC, DST, INA, and VUI. Functions with weak driving and dependence power are categorized under the autonomous quadrant. SCM is the only autonomous sustainable development function in this study. The linkage quadrant comprises functions with strong driving and dependence power. OSI, ETA, and STH are the linkage functions. It means they play a critical role in transferring the value of driver functions to dependent functions. As linkage functions, OSI, ETA, and STH are unstable, meaning any action on these functions would affect the other functions and, consequently, have a reflexive effect on themselves. For example, OSI would lead to open collaboration on the ETA that improves the human workforce's decision-making and information processing capabilities, from operators to managers. These valuable capabilities allow decision-makers to understand better the value of STH, encouraging them to allocate more resources and trust in open collaboration for sustainable innovation, which creates a loop enabling OSI. Within the ISM background, linkage elements and the resulting feedback loops are undesirable, especially when the outcome of the ISM is planned to serve as a theoretical basis for the regression-based structural model where feedback loops (connection cycles) are not acceptable. The ISM outcome in the present study is used to develop the strategy roadmap in which feedback loops pose no limitations. Overall, the presence of linkage variables in our study indicates that OSI, ETA, and STH are highly interdepended, and feedback loops exist among them. Thus, these functions should be developed simultaneously under the Industry 5.0 framework while considering their mutuality and complementarity. The dependent quadrant includes functions having weak driving power and strong dependence power. These functions are more complicated to develop since they rely upon linkage and driver functions to enable their development. BPM, UPR, RIN, SOP, CIP, ORE, and SCA are the dependent sustainable development functions of Industry 5.0.

5. Results and discussion

The interpretive model of Industry 5.0-enabled sustainable development and the MICMAC analysis collectively reveal that Industry 5.0 and the underlying digital industrial transformation facilitate the core objectives of sustainability, resilience, and human-centricity by first delivering the system integration and interoperability (SII) function. The integration part of the SII function involves combining all micro-modules of the hyperconnected digital ecosystem, such as computing systems, software packages, human operators, or smart devices, vertically and horizontally within and across smart components of Industry 5.0. The interoperability part of the SII function entails the ability of micro-modules of the smart components to communicate with and understand each other seamlessly (Sharma et al., 2022). SII offers important implications for various aspects of sustainable development, as the resulting decentralization provides all Industry 5.0 stakeholders with open, democratized, and pluralistic access to value (Fraga-Lamas et al., 2021b; Sindhwani et al., 2022). Fig. 4 shows that SII directly enables real-time communication (RTC) and value network integration (VUI). SII delivers this enabling role by facilitating data integrity, system access, and semantics clarity (Javaid et al., 2020; Thakur and Kumar Sehgal, 2021).

VUI refers to the vertical integration of all business processes and functions across various organizational layers and the horizontal

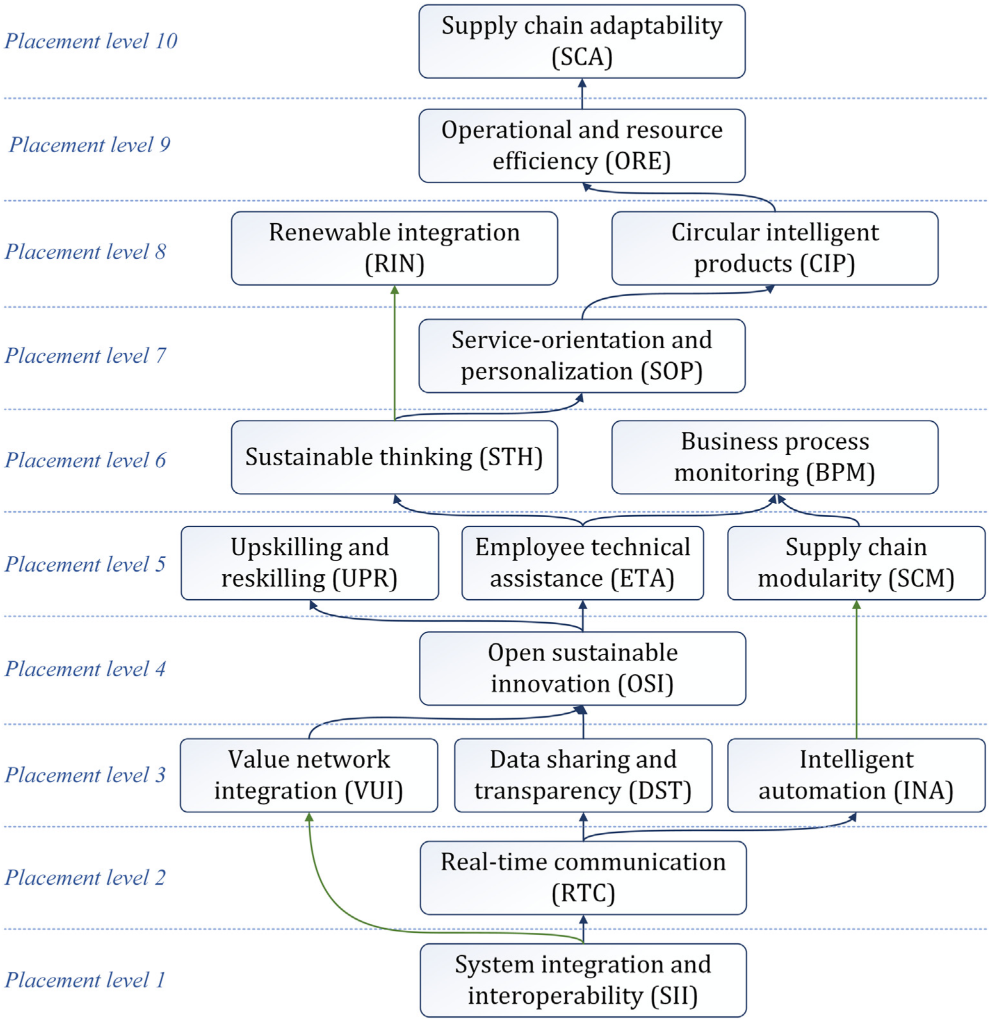
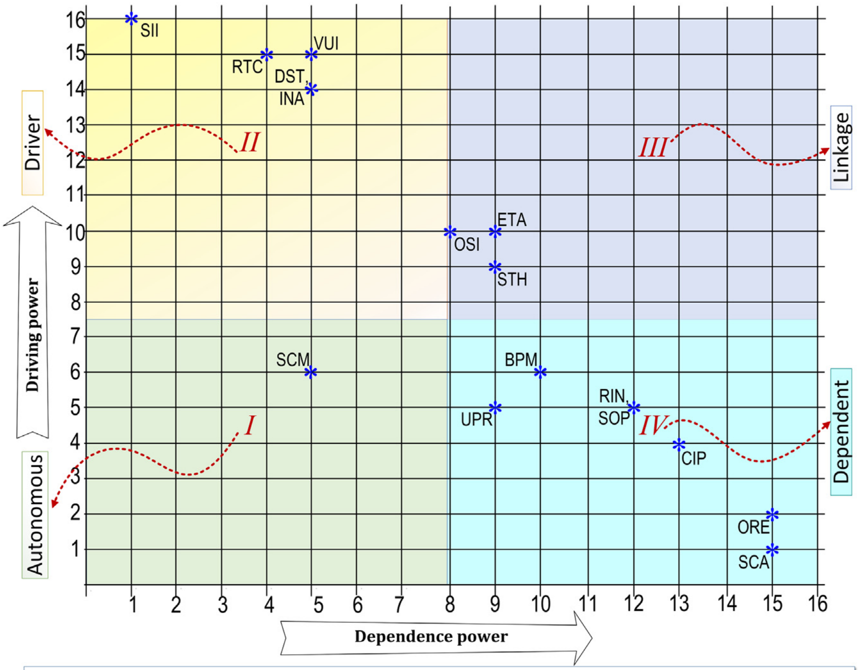


Fig. 4. The interpretive model of Industry 5.0-enabled sustainable development.

integration of supply chain processes involving seamless manufacturing, logistics, and distribution operations (Jabrane and Bousmah, 2021). Consistently, VUI requires the internal and external integration of Industry 5.0 smart components. VUI is closely tied to integrative technological constituents of Industry 5.0, such as CAI, CCPS, IoE, blockchain, and cloud computing (Longo et al., 2020). Product customization, manufacturing agility, process visibility, and improved trust and collaboration are outcomes of VUI essential to the sustainable development objectives of Industry 5.0 (Xu et al., 2021). The RTC function entails the ability of Industry 5.0 micro-modules to communicate and exchange data in real-time when necessary. The RTC function expands beyond the traditional real-time communication of production system components on the shopfloor, involving seamless communication of all value network modules (Javaid et al., 2020). Latest advancements in industrial communication (e.g., 5G or 6G), IoE, and AI-edge computing are crucial to addressing real-time communication requirements under Industry 5.0. RTC serves the sustainable development objectives of Industry 5.0 by improving production reliability, work environment safety, decision processes, risk management, and stakeholder responsiveness at the micro-organizational and value network levels (Saniuk et al., 2022).

Fig. 4 explains that RTC is critical to developing data sharing and transparency (DST) and intelligent automation (INA), functions that significantly rely on data timeliness, reliability, and dependability. DST is indispensable to Industry 5.0 as it addresses the data requirement of this data-driven phenomenon, allowing secure and reliable sharing of valuable data within organizational borders and across value networks (Özdemir and Hekim, 2018). Under the Industry 5.0 environment, DST ensures that the data is always accessible, communicable, and verifiable (Gorodetsky et al., 2020). More importantly, DST entails regulating data ownership and fair value return. IoE, blockchain, big data analytics, and cloud computing are critical enablers of DST under Industry 5.0 (Kumar et al., 2021). RTC supports the sustainable development objectives of Industry 5.0 by improving customer experience, value network visibility, value network collaboration, and environmental performance monitoring (Fatima et al., 2022). The INA function involves using disruptive automation technologies such as cognitive robots, CAI, intelligent business process management, and process automation to scale, automate, and streamline the decision-making processes across value network members (Nahavandi, 2019). Under Industry 5.0, INA's contribution to sustainable development objectives involves process simplification, resource productivity, industrial accident prevention, and environmental compliance (Fraga-Lamas et al., 2021b). More importantly, INA can augment the workforce, improve workplace safety, and enhance employee job satisfaction (Mladineo et al., 2021).

INA, in turn, enables the supply chain modularity (SCM) function. SCM draws on the digital supply network concept and aims to deliver scalable, agile, and customizable value networks. SCM involves decomposing complex value chains comprising smart adaptive factories, distribution channels, and suppliers into reconfigurable modules (Shao and Zavala, 2020). SCM allows industrial value chains to rearrange their modules according to the market needs and environmental circumstances and develop business models that support the core



Note: BPM, business process monitoring; CIP, circular intelligent products; DST, data sharing and transparency; ETA, employee technical assistance; INA, intelligent automation; ORE, operational and resource efficiency; OSI, open sustainable innovation; RIN, renewable integration; RTC, real-time communication; SCA, supply chain adaptability; SCM, supply chain modularity; SII, system integration and interoperability; SOP, service-orientation and personalization; STH, sustainable thinking; UPR, upskilling and reskilling; VUI, value network integration.

Fig. 5. Driving power and dependence power matrix.

objectives of Industry 5.0 through more equitable value distribution, product adaptation, and supply chain responsiveness (Dolgui et al., 2020). SCM relies on Industry 5.0 technologies that facilitate decentralization, allowing value network modules to make independent decisions and operate autonomously (Xu et al., 2021). CAI, CCPS, IoE, and edge/fog computing are examples of technologies vital to the SCM function (Maddikunta et al., 2022).

Through integrating value network operations and enabling transparent data sharing (VUI and DST functions), Industry 5.0 delivers the open sustainable innovation (OSI) function. This function delivery order is expected because OSI is data-intensive and requires close collaboration among value network members (Ghobakhloo et al., 2021b). OSI entails using Industry 5.0 technologies and techno-functional principles that support integrating open innovation into developing more sustainable products, processes, services, and business models (Demir and Cicibaş, 2019). IoE, cloud computing, and big data are essential to OIS since they integrate stakeholders' and consumers' green expectations into innovation processes (Carayannis and Morawska-Jancelewicz, 2022). Alternatively, smart CADM (e.g., additive manufacturing solutions), smart material, and dynamic simulation (e.g., digital twinning) transform the results of collaborative ideation and innovation into sustainable new products and processes (ElFar et al., 2021). Reduced energy consumption, improved societal impact, higher employee morale, and customer satisfaction are among the contributions of OSI to Industry 5.0 sustainable development values (Breque et al., 2021). Fig. 4 explains that OSI is the direct enabler of employee technical assistance (ETA) and upskilling and reskilling (UPR).

ETA entails using emerging technologies such as adaptive robots, smart wearables, and human interaction and recognition technologies (HIRT) that empower workforce-machine symbiosis. Instead of replacing employees with autonomous robots, ETA promotes human-centered approaches to industrial operations, such as the augmented or collaborative operator (Demir et al., 2019). Accordingly, ETA involves automating tedious and unergonomic tasks, providing employees with real-time information for better decision-making, and improving employees' competencies to interact with rapidly advancing digital industrial systems (Kaasinen et al., 2022). ETA mainly contributes to the socio-economic values of Industry 5.0, as it improves employees' productivity, health, work satisfaction, decision performance, and autonomy (Lu et al., 2022). UPR directly addresses the job displacement and unemployment concerns of Industry 4.0. UPR entails drawing on Industry 5.0 technologies and principles to devise and implement new human resource development programs that: (1) allow employees to learn new skills to address the existing talent gaps and (2) teach employees new skills that prepare them for new or alternate jobs caused by the ongoing digital transformation (Gürdür Broo et al., 2022). Industry 5.0 delivers UPR in various ways, such as using extended reality to improve training effectiveness, applying AI to optimize employee career pathing, or improving information and knowledge sharing within and across organizational boundaries (Kaasinen et al., 2022). UPR serves the sustainable development objectives of Industry 5.0 by addressing the ever-worsening skill crisis and improving employee morale, social inclusivity, and workforce performance (Carayannis and Morawska-Jancelewicz, 2022). By delivering ETA and SCM, Industry 5.0 paves the way for developing business process monitoring (BPM) and sustainable thinking (STH) functions.

The BPM function of Industry 5.0 involves analysing and reviewing business processes in real-time to identify existing and emerging critical process problems. BPM is multifaceted, including the functional monitoring of distributed business applications, technical monitoring of systems (e.g., hardware, software, or machinery), and process monitoring of business workflows (Maddikunta et al., 2022). Industry 5.0 delivers BPM via technologies and techno-functional principles that support real-time communication, decentralized decision-making, self-awareness/expressiveness, and human-machine integration (Nahavandi, 2019; Mladineo et al., 2021). Cost-saving, process scalability, improved employee experience, accountability, and customer satisfaction are examples of contributions that BPM can offer to the sustainable development values of Industry 5.0 (Paschek et al., 2022). The STH function requires businesses to place sustainable operations next to institutional survival as their primary organizational goals. Thus, STH involves drawing on Industry 5.0 technologies such as smart materials, HIRT, CADM, or intelligent product lifecycle management that allow businesses to develop and implement a systemic approach to integrate sustainability and create shared value for stakeholders (Renda et al., 2022). STH serves Industry 5.0 sustainable development goals by empowering businesses to integrate sustainability issues into the core business strategies and develop sustainable management practices that support resilience, environmental preservation, and human centricity (Carayannis and Morawska-Jancelewicz, 2022; Saniuk et al., 2022).

STH plays a critical role in facilitating the renewable integration (RIN) and service-orientation and personalization (SOP) functions of Industry 5.0. RIN refers to decarbonizing the energy sector by implementing and integrating renewable energy technologies into the energy supply chains (Kong et al., 2021). Although the price of these technologies has fallen significantly during the past few years, integrating renewable energy technologies is still challenged by technical barriers (such as energy variability or uncertainty) and administrative barriers such as lack of regulations and policies (ElFar et al., 2021). Industry 5.0 delivers the RIN function using CAI, dynamic simulation, IoE, decentralization, and other technologies and principles to improve energy production/storage capabilities, situational awareness, distribution management, load prediction, and resource generation forecasting. To deliver RIN, Industry 5.0 also facilitates collaboration among renewable energy stakeholders to facilitate supportive regulations and policy interventions (Carayannis et al., 2021). SOP involves developing more service-oriented business models, allowing products and assets of companies such as smart goods, production facilities, innovation capacity, or human capital to be offered to customers as possible services (ElFar et al., 2021; Gorodetsky et al., 2020). SOP also involves the large-scale production of customized (and even individualized) goods and services (Aslam et al., 2020). SOP is an ambitious function that relies on various technologies and techno-functional principles of Industry 5.0, such as horizontal/vertical integration, IoE, smart CADM, and cloud computing, to deliver the necessary value network integration and flexibility of the production processes (Johri et al., 2021; Sharma et al., 2022). SOP offers important implications for Industry 5.0 sustainable development values such as business resilience, customer satisfaction, resource efficiency, and product circularity (Saniuk et al., 2022). More importantly, SOP allows the development of the circular intelligent products (CIP) function.

The circular part of the CIP involves using Industry 5.0 technologies to design products that can function within the circular economy framework. CIP ensures that products are designed and developed to be environmentally friendly across their lifecycles (Fraga-Lamas et al., 2021a). Thus, CIP entails using smart materials, intelligent product lifecycle management, IoE, and smart CADM to develop products that eliminate waste, pollution, and emission and can be longer in use productively (Lenz et al., 2020). The intelligent part of CIP critically relies on materializing the smart product concept. Under Industry 5.0, a smart product can be featured as being sensor-equipped, AI-driven, and made of smart or engineered living materials (Li et al., 2021). Thanks to smart and circular products that can monitor and communicate their environmental footprint throughout the life cycle, CIP boosts Industry 5.0 sustainable development values concerning supply chain resilience, sustainable innovation, economic development, and environmental protection (Kumar et al., 2021; Sindhwani et al., 2022). Building on CIP, Industry 5.0 can deliver the operational and resource efficiency (ORE) function. This function involves using Industry 5.0 technologies and principles for industrial efficiency at various levels. For example, alert-driven IoE and CCPS systems can predict and prevent equipment-related production risks at the smart factory level (Xu et al., 2021). Alternatively, HIRT and smart wearables can empower employees to operate more productively and become more efficient at work. Automation, real-time communication, decentralization, and integrability features of Industry 5.0 further allow the digital supply networks to apply data-driven and actionable improvements throughout supply chain operations, optimizing resource consumption and reducing operational costs (Lu et al., 2022). The ORE function allows businesses to support the sustainable development objectives of Industry 5.0 by improving product accessibility, job creation, business agility, compliance, and circularity (Akundi et al., 2022; Nahavandi, 2019).

Finally, yet importantly, ORE complemented by the preceding functions delivers the supply chain adaptability (SCA) function of Industry 5.0. SCA entails drawing on Industry 5.0 features to proactively identify the structural shifts in the market and adjust the value network design, module compositions, and strategies accordingly (Maddikunta et al., 2022). It is intricate to develop SCA because of its extensive scope of impact and sheer dependence on other sustainable development functions (Renda et al., 2022). For instance, the product adjustment aspect of SCA involves using IoE, CADM, adaptive robots, and dynamic simulation to develop new products or rethink the existing ones according to shifting consumer preferences (Pettit et al., 2019). Alternatively, SCA requires supply chains to draw on CAI, cognitive computing, real-time communication, horizontal integration, and other constituents of Industry 5.0 to sense imminent disruption and proactively devise the best response strategies (Dolgui and Ivanov, 2022). SCA offers various implications for sustainable development values of Industry 5.0, primarily manifested in improving business, supply chain, and economic resilience (Sindhwani et al., 2022).

5.1. The roadmap to Industry 5.0-driven sustainability

The main objective of the study involved developing a roadmap describing how Industry 5.0 can function to enable sustainable development, especially in terms of resilience, environmental sustainability, and human-centricity. We identified the sustainability functions of Industry 5.0 by conducting a content-centric literature review. The interpretive model presented in Fig. 4 describes in which order these functions can best lead to promoting sustainability. These findings offer insights into the functionality of Industry 5.0 for sustainability and the necessary development sequences of functions. Nonetheless, Fig. 4 cannot be considered a sustainability roadmap since it falls short in interpreting the role of each function in promoting sustainable development goals of Industry 5.0 as well as the contextual relationships among each pair of functions. To develop the promised roadmap to the Industry 5.0-driven sustainability, we drew on the Interpretive Logic-knowledge base (ILB) developed based on the experts' opinions during the panel meetings. Fig. 6 represents the roadmap to the Industry 5.0-driven sustainability, which was developed based on integrating the ISM outputs with the ILB. In this figure, the direct relationships shown by vector arrows correspond to the contextual relationships identified within the initial reachability matrix (Table 3). This figure also assumes a direct relationship between each function and sustainable development. Placement levels in Fig. 6 correspond to the placement levels identified in the interpretive model (Fig. 4). Due to the complexity of the roadmap, the interpretation of each relationship has been explained in Table A2. This table corresponds to the ILB that recorded the collective opinions of experts regarding contextual relationships.

In general, the roadmap in Fig. 6 serves as a reference framework for Industry 5.0 actors involved in transforming industries toward sustainable development goals. This roadmap highlights the action plan for capitalizing on Industry 5.0 functions to gain sustainability values. Therefore, this roadmap assists with bridging the gap between the Industry 5.0 sustainability vision and the underlying actions and interactions that allow satisfying the intended sustainability objectives of this phenomenon. Technically speaking, this roadmap outlines the actions, interactions, and vision of Industry 5.0 for the future of the industry. It provides leaders, policy-makers, and Industry 5.0 actors the visual

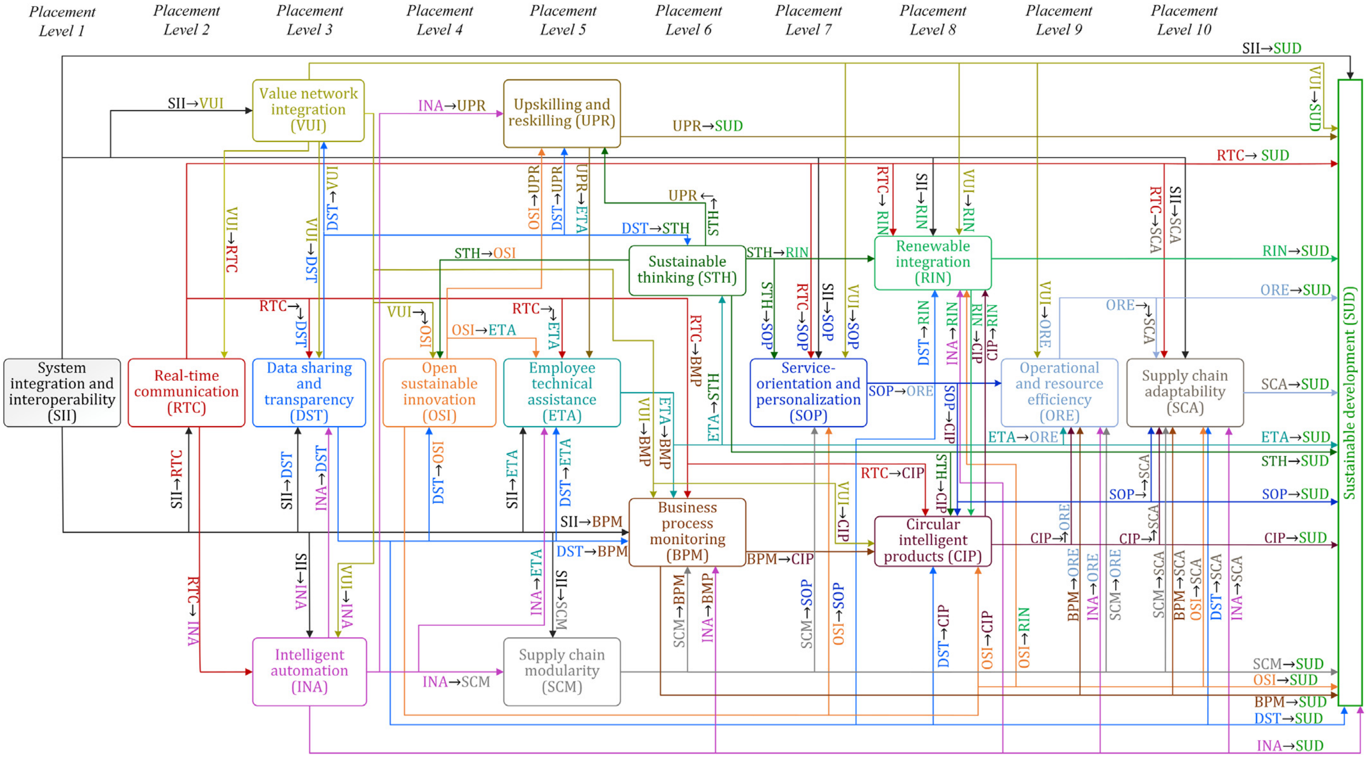


Fig. 6. The roadmap to Industry 5.0-driven sustainability.

representations of how each Industry 5.0 function should be developed or capitalized sequentially to maximize the sustainability values of Industry 5.0. For the present study, the vision is to deploy an industrial transformation framework titled Industry 5.0 to achieve sustainable development in ways that adhere to planetary and societal boundaries. The action part of the strategy roadmap manifests in the 16 sustainability functions of Industry 5.0, developed via consulting with the literature. The roadmap further demonstrates how actions (functions) should be sequentially developed to deliver the intended vision. The ISM methodology allowed us to explore and identify the precedence relationships among actions (16 functions) that collectively deliver the intended vision. More importantly, the strategy roadmap should generally explain the 'how' question related to the role of each action. In the present study, Table A2 and Fig. 6 collectively answer the how question, describing the internal enabling role of each sustainability function concerning other functions.

Results collectively reveal that each of the 16 functions provides essential and, in many cases, exclusive implications for promoting various micro and macro aspects of sustainable development. For example, ETA implications for sustainable development mainly involve promoting the micro-socioeconomic aspects of sustainability, such as enhancing employee productivity or improving workplace safety, satisfaction, and dignity. Alternatively, STH role in progressing sustainability entails improving macro socio-environmental sustainability aspects such as alleviating overconsumption or empowering Industry 5.0 stakeholders (e.g., social actors) to contribute to the circular economy or oversee the transitioning toward sustainable development. Table A2 reveals that while the functions identified provide key contributions to various aspects of sustainable development, their enabling role concerning the three core sustainability objectives of Industry 5.0 can be summarized as follows;

- Functions such as real-time communication, value network integration, intelligent automation, supply chain modularity, business process monitoring, service-orientation and personalization, operational and resource efficiency, and supply chain adaptability facilitate business, supply chain, and economic aspects of resilience;
- The environmental sustainability goals are mainly supported by value network integration, intelligent automation, sustainable thinking, renewable integration, circular intelligent products, and operational and resource efficiency;
- The human-centricity objectives of Industry 5.0 are mainly propelled by system integration and interoperability, data sharing and transparency, open sustainable innovation, upskilling and reskilling, employee technical assistance, and service-orientation and personalization.

Results presented in Fig. 6 and Table A2 reveal that the desirable contribution of Industry 5.0 to sustainable development entails the inclusive and sequential development of all sustainability functions. There are two major reasons for such inference. First, results show that each function can only address a few aspects of sustainable development. Indeed, functions complement each other to offer a broad spectrum of micro and macro-level economic, environmental, and social sustainability implications. Second, complex precedence relationships exist among sustainable development functions of Industry 5.0, and the sequence of their development would define how Industry 5.0 would lead to sustainable development values. For example, Table A2 shows that RTC enables SCA development, meaning supply chain adaptability builds on the foundation of supply chain-wide real-time communication. The enabling role of RTC for SCA involves the elimination of functional silos across the supply network or data-driven forecasting of imminent disruptions. While RTC does not offer direct implications for supply chain resilience, it plays a vital indirect role by increasing the adaptability of supply chains. Thus, collective and sequential development of Industry 5.0 functions, as identified within Fig. 6, is indispensable to sustainable development.

6. Conclusions

Experts believe that Industry 5.0 has emerged to complement Industry 4.0 and address the socio-environmental concerns of the ongoing digital industrial transformation. Industry 5.0 has been advertised to promote sustainable development. Nonetheless, it is unclear how Industry 5.0 can deliver its intended sustainable development values. To address this knowledge gap, the study conducted a content-centric synthesis of the literature and identified 16 functions through which Industry 5.0 can promote sustainable development values, especially in terms of resilience, environmental sustainability, and human-centricity. Notably, several of the functions identified, such as real-time communication or business process monitoring capabilities, are not exclusive to Industry 5.0, given that they have been associated with technological advancements since the third industrial revolution. However, The technological and regulatory advancements under Industry 5.0 redefines the width (quality) and breadth (scope) of these functions. The hyperconnected business ecosystems of Industry 5.0 and the stakeholder-centric features of this phenomenon allow the integrative development of these functions, building on their complementarities to offer additive values for achieving intended sustainable development goals.

The study further applied ISM and structured the relationships among the function into the Industry 5.0-enabled sustainable development model. This model describes how Industry 5.0 can extend beyond delivering efficiency and productivity to promote socio-environmental development meaningfully. The model and underlying findings are expected to offer theoretical and practical implications for academicians, industrialists, and policy-makers.

6.1. Implications

The study attempted to explain how Industry 5.0 can deliver its intended sustainable development values. For this purpose, the study first addressed the ambiguity surrounding this concept and developed a reference model that provided a holistic understanding of this phenomenon. The reference model showed that Industry 5.0 is a socio-technological phenomenon, which relies on technological advancements and stakeholder collaboration to go beyond economic development and address prevailing environmental and social concerns. Industry 5.0 is pushed by two major classes of technologies, including (1) enabling technologies that have matured since the third industrial revolution and have been vastly commercialized during Industry 4.0 and (2) emerging technologies representing the most disruptive technological innovations such as CAI or adaptive robots. The technological aspect of Industry 5.0 also involves developing the necessary techno-functional design principles, such as real-time capability or decentralization. These principles allow the technological constituents of Industry 5.0 to operate optimally and deliver their intended functionality. Contrary to Industry 4.0, which is often manifested in smart factories, the scope of Industry 5.0 expands well beyond the manufacturing industry and smartization of production facilities. Indeed, the sociocultural part of this phenomenon denotes the shift toward the stakeholder perspective while defining the components and scope of Industry 5.0. Smart customers, stakeholders (e.g., governments or labor unions), suppliers, adaptive production facilities, and technology providers are examples of the components that should digitalize and integrate to create the hyperconnected value ecosystem of Industry 5.0. The particularity of Industry 5.0 components changes according to business and industrial context. For example, smart patients, pharmaceutical firms, physicians, hospitals, and insurance companies constitute the components of Healthcare Industry 5.0, also known as Health 5.0.

The study identified 16 functions through which Industry 5.0 can promote sustainable development goals. These functions are the byproduct of the interaction among technology, principle, and component layers of the Industry 5.0 reference model. Results revealed that each function could independently contribute to some sustainable development objectives of Industry 5.0. For example, the data sharing and transparency (DST) function can promote supply chain visibility, traceability, and transparency features vital to the supply chain resilience objective of Industry 5.0. Nevertheless, there is substantial complementarity among the functions identified, and collective development of all functions and resulting synergies would offer super-additive values for sustainable development objectives of Industry 5.0. Notably, ISM results showed that complex precedence relationships exist among the functions identified, which means these functions are developed sequentially in a specific order. Indeed, the sequence of relationships identified in Fig. 4 and Fig. 6 can be valuable to scholars, policy-makers, and even industrialists, empowering them to strategically govern the technology-driven digital industrial transformation under Industry 5.0 to promote sustainable development.

The interpretive model in Fig. 4 and the MICMAC results show that Industry 5.0 contribution to sustainable development should first involve using system integration and interoperability features of this phenomenon to enable real-time communication among Industry 5.0 micro-components (e.g., operations technologies, information technologies, operators, embedded systems, or processes). These functions should be further leveraged for value network-wide process integration, data sharing, and intelligent automation. By doing so, value networks can integrate, exchange information, and transparently collaborate to promote open sustainability innovation. By introducing sustainability into innovation processes, value network partners should further leverage Industry 5.0 features to modularize the supply chain design, develop smart workspace and employees, and increase the versatility and specialization of human resources to meet Industry 5.0 skill requirements. Meeting these conditions would allow integrating sustainable thinking into business strategies to balance economic gains and socio-environmental commitments. For this to happen, supply partners should proactively monitor core business processes and functions to analyze their economic and socio-environmental performance and risks. Developing these functions should allow businesses to integrate renewable energy (e.g., via AI-driven microgrids) and move toward servitization and product individualization to develop new value streams and improve customer experience. In doing so, businesses should leverage Industry 5.0 technologies, principles, and functions to develop circular intelligent products that allow self-mapping of their entire lifecycle to integrate into the circular economy. These functions would eventually allow businesses to increase their resource and operational efficiency, thus, improving economic growth and reducing waste, energy consumption, and emission. Finally, these functions allow industrial value chains to gain the necessary agility, resources, capabilities, expertise, and innovation capacities to adapt to the structural shifts in the market caused by disruptions and gain the necessary resilience.

The precedence relationships identified across the ISM analysis represent the natural order in which the sustainable development functions of Industry 5.0 should be developed. The driver functions, placed at the lower levels of the structural model, are more critical because businesses should leverage them to develop more dependent functions such as ORE or SCA. Nonetheless, the absolute value of dependent functions cannot be overlooked, given that they are indispensable to the sustainable development objectives of Industry 5.0. Although many of the functions identified are not exclusive to Industry 5.0, this phenomenon draws on its technological constituents, techno-functional design principles, and smart components to build a transition path that allows inclusive development of all functions in the identified order. Therefore, the Industry 5.0-enabled roadmap to sustainable development represents a transformation framework that learns from Industry 4.0 shortcomings and Covid 19 disruption to design a hyperconnected industrial ecosystem that is inherently productive, resilient to future shocks, human-centered, and socio-environmentally sustainable.

To summarize, the roadmap and underlying results are believed to offer the following contributions to the theory and practice:

- Industry 5.0 can contribute to sustainable development via 16 interdependent functions. These functions vary significantly in their purpose and properties, ranging from micro-technical functions like real-time communication to macro-operational functions like supply chain adaptability.
- Each of the functions provides important but exclusive implications for promoting sustainability. These functions complement each other in promoting various aspects of sustainable development. Thus, none of the functions can be overlooked, regardless of their enabling role or dependability.
- Significant precedence relationships were identified among the sustainability functions of Industry 5.0. Therefore, these functions should be developed and capitalized sequentially and in the specific order described within the structural model. The synergies arising from the sequential development of these functions maximize the possible sustainability gain of the Industry 5.0 framework.
- Although some of the identified functions are not exclusive to this phenomenon, Industry 5.0 offers a digital transformational ecosystem that allows the synchronized and conclusive development of these ambitious functions.

6.2. Limitations and future research directions

Overall, the present study identified functions through which Industry 5.0 might potentially deliver its intended sustainable development values. The study modeled the sequence in which these functions should be developed based on the ISM technique and further identified their possible interactions. While we followed the standard methodology to develop our interpretive model and strategy roadmap, the following limitations should be taken into consideration while interpreting the results:

- The roadmap is limited to the contextual properties under which it has been developed, particularly concerning the experts' demographics.
- Although the study identified the sequential relationships between each pair of functions, it could not conclusively determine the strength of the relationships, mainly due to the limitation of the ISM methodology.
- The functions introduced root in the early contributions of the literature to the Industry 5.0 phenomenon. This topic is new and evolving, and literature on Industry 5.0 is equally embryonic. We expect the width and breadth of the Industry 5.0 sustainability functions to grow in the future considerably.
- The study explained how Industry 5.0 could function in promoting sustainable development. Nonetheless, it was unconscionable for the present study to explain how industries and businesses should transform from Industry 4.0 or even older industrial frameworks to Industry 5.0.

In addition, and despite our efforts, much is unknown about how this phenomenon will unfold in the future. Thus, future research is invited to extend our work in the following manners. Due to methodological constraints, we merely drew on the opinions of European experts to identify the contextual relationships among the functions. Although Industry 5.0 is primarily a European initiative, we expect it to become a global reality as Industry 4.0 once did. Using the opinion of a broader spectrum of experts from various socio-economic contexts and resynthesizing the relationships among the sustainable development functions of Industry 5.0 can serve as an important avenue for future research.

While we acknowledge that Industry 5.0 has the capacity to promote sustainable development, it is not a self-propelled phenomenon. Indeed, our model described a hypothetical best-case scenario where all necessary conditions for materializing Industry 5.0 were in place. Although the transition toward this phenomenon has already begun, especially in Europe as well as in Japan (under Society 5.0), the materialization and success of Industry 5.0 rely on several necessary actions and vital requirements. Industry 5.0 requires the implementation of necessary technologies, mainly emerging technological innovations. While industry leaders excel in this area, industrial reports indicate that average businesses, particularly smaller ones, still struggle with implementing basic Industry 4.0 technologies. This condition requires inclusive technology diffusion initiatives across various regions and industries to empower impartial and fair technological advancement of value networks. However, Industry 5.0 is in its infancy, and such a supportive technological development agenda appears to be lacking. Future research is invited to explore how Industry 5.0 technology development and implementation roadmap should be developed to support open innovation, shared research, and collaborative technology diffusion initiatives across regions. In addition, Industry 5.0 is partly a technology-driven phenomenon, which relies on value network-wide integration, interconnectivity, and data-driven operations. The high pace of digital transformation under Industry 5.0 renders cybersecurity a vital enabler of this phenomenon. The width and breadth of cyber risks under Industry 5.0 call for future research on secure and resilient approaches to cybersecurity.

The reference model identified the crucial role of Industry 5.0 stakeholders, explaining that transition into this phenomenon entails supportive policies in several areas, such as society, culture, innovation, education, government operations, energy, economic affairs, environment, and taxation. The collective and synergetic development of these policies falls outside the remit of individual stakeholders (e.g., governments or labor unions), requiring bilateral and, in many instances, multilateral cooperation among Industry 5.0 stakeholders. The underlying mechanism through which stakeholders can collaborate to develop meaningful Industry 5.0 supportive policies and regulations is largely unknown. Therefore, identifying how the power of public-private stakeholder collaboration can be harnessed for shaping Industry 5.0 supportive policies, initiatives, and regulatory frameworks represents an important avenue for future research.

Finally, yet importantly, experts believe that much like the Government 5.0 concept signifying the government's new role in promoting Industry 5.0, this phenomenon requires a new form of corporate governance. Indeed, Corporate Governance 5.0 is indispensable since the Industry 5.0 transition requires corporations to fundamentally change their mindset, strategies, and objectives. Under Industry 5.0, businesses should transition from shareholder primacy to stakeholder capitalism, emphasizing less on short-term economic gains and prioritizing shared value. This requires aligning corporate initiatives with Industry 5.0 sustainable development objectives, deliverable via a transformative corporate governance model. While there is a general agreement on the necessity of Corporate Governance 5.0, there is little to no understanding of how such sustainable corporate governance frameworks could be developed. Future research can address this knowledge gap by conducting in-depth analyses of how businesses can integrate sustainable development values of Industry 5.0 into their corporate strategies and develop measurable indices to assess their progress toward those values.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Self-assessment questionnaire

1. How familiar do you consider yourself with the Industry 5.0 framework proposed by the European Commission?
2. How familiar do you consider yourself with Industry 5.0 scientific and industrial background?
3. How familiar do you consider yourself with the mechanisms through which Industry 5.0 can promote sustainable development?
4. Please briefly explain your past collaboration with the European Commission that might somehow relate to Industry 5.0-driven sustainability (Examples may include collaboration as principal investigator, senior researcher, or advisory board on related topics such as technology governance, digital transformation, Industry 4.0, sustainability, digitally-driven circular economy, or resilient economy).
5. Your contribution would involve participating in six online expert panel meetings. Each meeting would approximately take 70 min. Assuming that the meeting dates would be tailored to your schedule, how likely would it be for you to commit to every single expert panel meeting?
6. How would you rate your English proficiency for engaging in oral and written discussions across the six expert panel meetings?

Table A1
Hierarchy level for sustainable development functions of Industry 5.0.

Function	Reachability set	Antecedent set	Intersection set	Extraction level
Iteration 1				
BPM[a]	BPM, CIP, ORE, RIN, SCA, SOP	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	BPM	
CIP	CIP, ORE, RIN, SCA	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	CIP, RIN	
DST	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCA, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	BPM, CIP, ETA, ORE, OSI, RIN, SCA, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
INA	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, SCA, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
ORE	ORE, SCA	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCM, SII, SOP, STH, UPR, VUI	ORE	
OSI	BPM, CIP, ETA, ORE, OSI, RIN, SCA, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, VUI	ETA, OSI, STH	
RIN	CIP, ORE, RIN, SCA, SOP	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SII, SOP, STH, VUI	CIP, RIN, SOP	
RTC	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCA, SCM, SOP, STH, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCA	SCA	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCA, SCM, SII, SOP, STH, VUI	SCA	*1*
SCM	BPM, CIP, ORE, SCA, SCM, SOP	INA, RTC, SCM, SII, VUI	SCM	
SII	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCA, SCM, SII, SOP, STH, UPR, VUI	SII	SII	
SOP	CIP, ORE, RIN, SCA, SOP	BPM, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	RIN, SOP	
STH	CIP, ETA, ORE, OSI, RIN, SCA, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
UPR	BPM, ETA, ORE, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, STH, UPR	
VUI	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCA, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 2				
BPM	BPM, CIP, ORE, RIN, SOP	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	BPM	
CIP	CIP, ORE, RIN	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	CIP, RIN	
DST	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	BPM, CIP, ETA, ORE, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
INA	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
ORE	ORE	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCM, SII, SOP, STH, UPR, VUI	ORE	*2*
OSI	BPM, CIP, ETA, ORE, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, VUI	ETA, OSI, STH	
RIN	CIP, ORE, RIN, SOP	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SII, SOP, STH, VUI	CIP, RIN, SOP	
RTC	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCM, SOP, STH, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCM	BPM, CIP, ORE, SCM, SOP	INA, RTC, SCM, SII, VUI	SCM	
SII	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCM, SII, SOP, STH, UPR, VUI	SII	SII	
SOP	CIP, ORE, RIN, SOP	BPM, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	RIN, SOP	
STH	CIP, ETA, ORE, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
UPR	BPM, ETA, ORE, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, STH, UPR	
VUI	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 3				
BPM	BPM, CIP, RIN, SOP	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	BPM	
CIP	CIP, RIN	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	CIP, RIN	*3*
DST	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	BPM, CIP, ETA, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
INA	BPM, CIP, DST, ETA, INA, OSI, RIN, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
OSI	BPM, CIP, ETA, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, VUI	ETA, OSI, STH	
RIN	CIP, RIN, SOP	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SII, SOP, STH, VUI	CIP, RIN, SOP	*3*

Table A1 (*continued*)

Function	Reachability set	Antecedent set	Intersection set	Extraction level
RTC	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SOP, STH, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCM	BPM, CIP, SCM, SOP	INA, RTC, SCM, SII, VUI	SCM	
SII	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, UPR, VUI	SII	SII	
SOP	CIP, RIN, SOP	BPM, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	RIN, SOP	
STH	CIP, ETA, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
UPR	BPM, ETA, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, STH, UPR	
VUI	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 4				
BPM	BPM, SOP	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	BPM	
DST	BPM, DST, ETA, INA, OSI, RTC, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	BPM, ETA, OSI, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
INA	BPM, DST, ETA, INA, OSI, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
OSI	BPM, ETA, OSI, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, VUI	ETA, OSI, STH	
RTC	BPM, DST, ETA, INA, OSI, RTC, SCM, SOP, STH, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCM	BPM, SCM, SOP	INA, RTC, SCM, SII, VUI	SCM	
SII	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, SOP, STH, UPR, VUI	SII	SII	
SOP	SOP	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, SOP, STH, VUI	SOP	*4*
STH	ETA, OSI, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
UPR	BPM, ETA, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, STH, UPR	
VUI	BPM, DST, ETA, INA, OSI, RTC, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 5				
BPM	BPM	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	BPM	*5*
DST	BPM, DST, ETA, INA, OSI, RTC, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	BPM, ETA, OSI, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
INA	BPM, DST, ETA, INA, OSI, SCM, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
OSI	BPM, ETA, OSI, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, VUI	ETA, OSI, STH	
RTC	BPM, DST, ETA, INA, OSI, RTC, SCM, STH, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCM	BPM, SCM	INA, RTC, SCM, SII, VUI	SCM	
SII	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, STH, UPR, VUI	SII	SII	
STH	ETA, OSI, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	*5*
UPR	BPM, ETA, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, STH, UPR	
VUI	BPM, DST, ETA, INA, OSI, RTC, SCM, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 6				
DST	DST, ETA, INA, OSI, RTC, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	ETA, OSI, UPR	DST, ETA, INA, OSI, RTC, SII, UPR, VUI	ETA, OSI, UPR	*6*
INA	DST, ETA, INA, OSI, SCM, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
OSI	ETA, OSI, UPR	DST, ETA, INA, OSI, RTC, SII, VUI	ETA, OSI	
RTC	DST, ETA, INA, OSI, RTC, SCM, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCM	SCM	INA, RTC, SCM, SII, VUI	SCM	*6*
SII	DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	SII	SII	
UPR	ETA, UPR	DST, ETA, INA, OSI, RTC, SII, UPR, VUI	ETA, UPR	*6*
VUI	DST, ETA, INA, OSI, RTC, SCM, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 7				
DST	DST, INA, OSI, RTC, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
INA	DST, INA, OSI, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
OSI	OSI	DST, INA, OSI, RTC, SII, VUI	OSI	*7*
RTC	DST, INA, OSI, RTC, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SII	DST, INA, OSI, RTC, SII, VUI	SII	SII	
VUI	DST, INA, OSI, RTC, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 8				
DST	DST, INA, RTC, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	*8*
INA	DST, INA, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	*8*
RTC	DST, INA, RTC, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SII	DST, INA, RTC, SII, VUI	SII	SII	
VUI	DST, INA, RTC, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	*8*

(*continued on next page*)

Table A1 (*continued*)

Function	Reachability set	Antecedent set	Intersection set	Extraction level
Iteration 9				
RTC	RTC	RTC, SII	DST	*9*
SII	RTC, SII	SII	SII	
Iteration 10				
SII	SII	SII	SII	*10*

[a] Note: BPM, business process monitoring; CIP, circular intelligent products; DST, data sharing and transparency; ETA, employee technical assistance; INA, intelligent automation; ORE, operational and resource efficiency; OSI, open sustainable innovation; RIN, renewable integration; RTC, real-time communication; SCA, supply chain adaptability; SCM, supply chain modularity; SII, system integration and interoperability; SOP, service-orientation and personalization; STH, sustainable thinking; UPR, upskilling and reskilling; VUI, value network integration.

Table A2
Interpretive logic-knowledge base matrix for sustainable development functions of Industry 5.0.

Contextual relationship	Enabling role
System integration and interoperability (SII)	
SII → BPM	Streamlined problem situation detection; streamlined data transfer via various interfaces
SII → DST	Reduced data hoarding; data scalability and availability; improved data visibility
SII → ETA	Improved employee-machine integration; improved data accessibility of operators; better understanding and capturing of human elements in unstructured/structured data contexts
SII → INA	Integration of intelligent process components; better integration of AI and robotic process automation modules
SII → RIN	Better integration of energy generation technologies; integration of adaptive energy storage technologies; integration of hybrid energy generation and delivery technologies
SII → RTC	Improved data packet priority prioritization; Improved communication paths, availability, and fault tolerance
SII → SCA	Information accessibility across the value network; improved connectivity with cloud infrastructure; improved synchronization and connectivity of data collection, transformation, aggregation, and analytics layer
SII → SCM	Improved supply chain module monitoring; improved customer and supplier module integrability; elimination of data silos, and improved data integrity
SII → SOP	Improved accessibility and aggregation of supply chain-wide contextual data
SII → VUI	Integrability and connectivity of smart products, machinery, production facilities, warehousing infrastructure, smart customers, and distribution modules
SII → SUD	Integration of human-centered technologies; deployment of distributed energy resources; better integration of customer preferences; IT/OT operational efficiency
Real-time communication (RTC)	
RTC → BPM	Real-time monitoring of application and technical related business functions; real-time monitoring of technical infrastructure and data transfer
RTC → CIP	Real-time monitoring and analysis of product life cycle performance; real-time collaborative product visualization and design; facilitating reuse and recycling via real-time product structure record management
RTC → DST	Real-time visibility of organizational assets; instant access to modular data points; accessibility of hard-to-get data across the value network; business agility; improved business disruption sensing
RTC → ETA	Improved human-information processing capabilities; improved man-machine interconnection and integration; real-time monitoring and recognition of working environment conditions
RTC → INA	More efficient accessing and analysis of structured and unstructured data; better leveraging of AI insights for handling complex tasks; closed-loop real-time data exchange between automation subsystem
RTC → RIN	Real-time grid integration of renewable energy sources; visibility into renewable energy generation infrastructure; real-time energy pricing management; real-time energy source availability assessment
RTC → SCA	Data-driven early trend and disruption forecasting; data accessibility across supply chain modules; streamlined end-to-end process risk assessment; eliminating information and functional silos across the supply network
RTC → SOP	Transitioning toward service-oriented business models such as product-as-a-service or cloud manufacturing; introduction of smart products to the business model
RTC → SUD	Real-time risk and failure monitoring; real-time environmental performance assessment; improved customer experience
Value network integration (VUI)	
VUI → BPM	Value network-wide detection and management of process disruptions; improved quality and performance of business process execution across the supply network
VUI → CIP	Interorganizational communication of knowledge concerning the design, features, performance, and end-of-life plans of smart sustainable products; integration of smart sustainable product innovation into business models
VUI → DST	Improved information access; streamlined information flow across supply partners and customers; trust-driven information sharing; higher data reliability
VUI → INA	Supply chain-wide intelligence and automation investment alignment; collaborative automation and digitalization strategic planning; shared resources for intelligent automation
VUI → ORE	Clear communication among various supply chain functions; streamlined supply chain planning; supply chain waste reduction (e.g., via warehousing efficiency, reduction of time to market, or higher operational reliability)
VUI → OSI	External collaboration for improving ideation and problem-solving capabilities; improved customer exploration, collaborative ideation, and developing actionable plans for addressing customer needs
VUI → RIN	Flexible response to energy supply-demand balance variability and uncertainty; security of renewable energy supply; collaborative renewables procurement strategies; collaborative renewable investment risk management
VUI → RTC	Interoperability of independent logistics and supply chain modules/subsystems; standardization of communication protocols
VUI → SOP	Customer-oriented collaborative product design; cost-efficiencies through supply chain optimization; improved customer management and access to customer and product behavior data
VUI → SUD	Resource consumption efficiency; supply chain resilience; sustainability talent management; material flow efficiency; waste and pollution reduction; circular production and supply chain
Data sharing and transparency (DST)	
DST → BPM	Transparency of end-to-end processes based on predefined key performance indices; visibility into business operations, and early detection of process disruptions
DST → CIP	Improved information sharing and collaboration among circular product development teams; facilitating circular consumption models such as collaborative

Table A2 (*continued*)

Contextual relationship	Enabling role
	consumption
DST → ETA	Information-driven employee empowerment; improved decision-making capabilities of employees
DST → OSI	Streamlined idea and intellectual property sharing for collaborative innovation; development of open idea ecosystems
DST → RIN	Better communication of benefits and impacts of renewable integration to stakeholders; visibility into impacts, costs, and difficulties associated with various reviewable integration strategies; streamlined partnership for reviewable innovation and growth
DST → SCA	Supply chain openness to change; proactive supply chain threat/disruption discovery and analysis; streamlined stakeholder interactions and integration for better adapting to dynamic environmental (especially new market) conditions
DST → STH	Communication of prevailing sustainability challenges; understanding of the need for transitioning from neoliberal capitalism and profit-centricity toward more shareholder primacy and circular economic models
DST → UPR	Better highlighting of the value of upskilling and reskilling; breaking resistance toward learning among the workforce; communicating the objectives and benefits of training programs; better alignment of the human resource team with training requirements
DST → VUI	Building trust in supply chain relationships; accessibility of factual information concerning various internal and external supply chain operations; elimination of information and functional silos; shared development of integration goals and performance metrics
DST → SUD	Customer reassurance and satisfaction; improved stakeholder partnership; productivity-driven competitive advantage; ethical value creation and fighting child/forced labor; sustainability performance monitoring; sustainability skill gap identification
Intelligent automation (INA)	
INA → BPM	Improved integration with process architecture part under the enterprise systems; better integration with process engines for process monitoring; improved cognitive capabilities of employees
INA → DST	Automated data collection, processing, and exchange; reduced data errors; improved data security; data clarity and accuracy; improved energy demand-side management
INA → ETA	Automation of repetitive and labor-intensive tasks; improved employee experience, engagement, and empowerment; increasing employee performance while minimizing human errors
INA → ORE	Higher process efficiency; optimization of back-office operations; operational risk and failure reduction; customer service productivity; reduction of end-to-end business process times
INA → RIN	Automation of renewable equipment production; improved consumption and demand forecasting via integrated application of self-learning models, historical/real-time sensor-driven data, and cloud information; improved grid management
INA → SCA	Improved supply chain resource orchestration; reconfigurability of supply chin modules and system components; automation, decentralization, and integration of decision processes
INA → SCM	Decentralized decision-making capability of supply chain modules; autonomous data transfer among disparate supply chain systems; improved responsiveness of supply chain modules
INA → UPR	Identification of training priorities; autonomous and data-driven identification and forecasting of skill gaps; data-driven development of career development paths; autonomous skill assessment
INA → SUD	Improving operational efficiency; economic transparency; facilitating energy transition; waste and emission reduction; more resilient industrial operations; resource productivity
Open sustainable innovation (OSI)	
OSI → CIP	Communicating sustainability objectives and knowledge across the value network; commercial development and implementation of cleaner and energy-aware operations technology, non-polluting raw material, remanufactured components, and recycled material
OSI → ETA	Development and implementation of employee (operator) assist technologies; prioritizing human-centric approaches to business, operations, and technology management
OSI → RIN	Open collaboration for promoting renewables innovation; innovation for structural development for renewables localization and integration; collective investment in renewables research and development; leveraging external knowledge by stakeholders to increase renewables innovation performance
OSI → SCA	Supply chain-wide audit of sustainability initiatives; demand-driven and collaborative eco-friendly product and process innovation
OSI → SOP	Customer-centric innovation; open collaboration for customer-oriented product and process innovation; re-vectoring business model for implementing servitization strategies
OSI → UPR	Strategies for developing necessary skillsets for long-term employability; development of employee-friendly training technologies and platforms
OSI → SUD	Improved customer satisfaction, experience, and rights; employment growth; equal employment opportunity; sustainable partnership; sustainable innovation growth
Upskilling and reskilling (UPR)	
UPR → ETA	Improving employees' capability to integrate and interact with emerging disruptive technologies; enhancing employees' technological self-efficacy and self-realization
UPR → SUD	Improved workforce digital literacy; reduction of job complexity; improved job security; reducing skill discrepancies; income equality; new employment opportunities; minimizing job displacement
Employee technical assistance (ETA)	
ETA→ BPM	Better access to employee performance data for business process optimization; improved employee tracking for preventing errors and risks
ETA→ ORE	Higher employee productivity; workforce time efficiency; reduction of human errors; efficient decision making
ETA→ STH	Improved sustainability decision processes; providing employees with valuable sustainability knowledge; enhancing the sustainability-oriented absorptive capacity of individuals
ETA→ SUD	Improving working environment; workplace dignity; improved job satisfaction; reduced work accidents; employee productivity
Supply chain modularity (SCM)	
SCM → BPM	Decentralized monitoring procedures across technical components; faster problem identification and proactiveness in addressing risks and problems; flexibility in addressing process disruptions
SCM → ORE	Faster infrastructural and product adaptation to market turbulence; operational agility and scalability; reduction of supply chain complexity
SCM → SCA	Higher responsiveness of logistics processes and operations; supply chain flexibility and agility; adaptable supply chain capabilities
SCM → SOP	Production infrastructure flexibility and reconfigurability for rapid integration of new product designs; adaptability of sourcing and delivery channels to the shifting consumer preferences and demands
SCM → SUD	Supply chain resilience; supply chain productivity and profitability
Sustainable thinking (STH)	
STH → CIP	Capacity to involve critical stakeholders in sustainable product innovation; identifying the product sustainability priorities and developing necessary initiatives; collaborative sustainability benchmarking of smart products

(continued on next page)

Table A2 (*continued*)

Contextual relationship	Enabling role
STH → OSI	Cleaner objectives for innovation externalization; positive attitude toward collaborative innovation; improved commitment and participation; supportive public-private partnerships
STH → RIN	Sectorial, regional, and international innovation system approaches to supporting renewables; developing a comprehensive policy mix for supporting energy system transformation toward renewables; prioritizing reviewable integration by individual consumers, business units, and supply networks
STH → SOP	Inclusive change management for processes, technologies, and people; developing actionable objectives for the development of connected and customer-oriented products and processes; collaborative market sensing for smart, sustainable, and customizable products and services
STH → UPR	Equitable reskilling and upskilling opportunities; supportive policies for promoting skilling and upskilling training opportunities; introducing reskilling and upskilling as social-economic responsibility
STH → SUD	Equipping social actors with knowledge, competencies, skills, values, and behavior for contributing to the sustainable and circular economy; alleviating overconsumption; Social actors' engagement in monitoring the progress of sustainable development goals
Business process monitoring (BPM)	
BPM → CIP	Improved end-of-life product recovery; higher reliability and quality of smart sustainable products; improved prototyping and mass production of smart sustainable products; performance monitoring of smart sustainable products
BPM → ORE	Identifying and addressing root causes of performance issues; lower equipment and machinery downtime; avoiding legal liabilities; reduced material and energy variability; higher product quality
BPM → SCA	Efficiency of reactive and proactive decision-making processes; proactive and data-driven demand responsiveness; better forecasting of supply chain disruption scope and scale of impact; better monitoring and control of supply chain risk and failure factors
BPM → SUD	Improved resilience against business disruptions; end-to-end environmental transparency of business operations; risk and waste-averse business processes; safer and smarter working environment
Service-orientation and personalization (SOP)	
SOP → CIP	Acceptance of new smart sustainable products by customers; improved data acquisition, mapping, and profiling of smart products for sustainability performance improvement
SOP → ORE	Demand reliability; on-demand scalability; efficiency of customer service; marketing efficiency; cash flow reliability
SOP → SUD	Improved energy and material consumption; business resilience; customer satisfaction; new employment opportunities; improved customer experience; promoting circular economy
Renewable integration (RIN)	
RIN → CIP	Less carbon-intensive products; ease of end-of-life recovery, recycling, remanufacturing, or repurposing
RIN → SUD	Preventing environmental degradation; pollution and emission reduction; regional economic development; localized value generation; inclusive and equitable energy accessibility
Circular intelligent products (CIP)	
CIP → ORE	Extended product life cycle; improved product recyclability or reusability; product development or updating efficiency; streamlined product maintenance and after-sale services
CIP → RIN	Integrability with modular renewable energy systems; synchronization of energy consumption needs with renewable energy grids
CIP → SCA	Data-driven forecasting of consumers' future demand and preferences; more adaptable business models; better sensing of imminent market disruptions or opportunities
CIP → SUD	Energy consumption efficiency; prolonged product life-cycle; promoting consumer digital literacy; emission reduction; waste reduction; improved end-of-life recovery
Operational and resource efficiency (ORE)	
ORE→ SCA	Operational cost efficiency; operational agility in implementing the necessary change processes and action plans; product mix adaptability and expandability
ORE→ SUD	Improved resource and energy footprints of industrial operations; economic, supply chain, and business-level resilience; reduction of industrial and post-consumer waste; reduced rebound effect; facilitating circular economy
Supply chain adaptability (SCA)	
SCA → SUD	Economic resilience; supply chain productivity; job security and stability; improved product accessibility; sustainable supply chain processes

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