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Industry 4.0 applications for sustainable manufacturing: A systematic literature review and a roadmap to sustainable development

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ABSTRACT

Industry 4.0 is transforming the manufacturing industry and the economics of value creation. A great deal of positive hype has built up around the sustainable development implications of Industry 4.0 technologies during the past few years. Expectations regarding the opportunities that Industry 4.0 offers for sustainable manufacturing are significantly high, but the lack of accurate understanding of the process through which Industry 4.0 technologies enable sustainable manufacturing is a fundamental barrier for businesses pursuing digitalization and sustainable thinking. The present study addresses this knowledge gap by developing a roadmap that explains how Industry 4.0 and the underlying digital technologies can be leveraged to support and facilitate the triple bottom line of sustainable manufacturing. To this purpose, the study conducted a systematic literature review and identified 15 sustainability functions through which Industry 4.0 contributes to sustainable manufacturing. Interpretive structural modeling was further applied to identify the relationships that may exist within the sustainability functions. The resulting sustainable manufacturing roadmap explains how, and in which order, various Industry 4.0 sustainability functions contribute to developing the economic, environmental, and social dimensions of sustainability. The resulting implications are expected to serve manufacturers, industrialists, and academia as a strategic guide for leveraging Industry 4.0 digital transformation to support sustainable development.

1. Introduction

Manufacturers worldwide struggle with the gradual increase in compliance, energy, and material costs, on top of stakeholders' higher sustainability expectations (Jena et al., 2020). Sustainable manufacturing and operating in a more sustainably responsible manner are business imperatives for manufacturing competitiveness (Margherita and Braccini, 2020). World-class manufacturers have already taken necessary steps for better contributing to economic and socio-environmental development. The industrial report largely shows that sustainable manufacturing pioneers have been presented with better profit-making opportunities and improved competitiveness. On the other hand, smaller manufacturers have been mostly unable to embrace sustainable manufacturing opportunities (OECD, 2020). They usually struggle with short-term survival, particularly under excessive market turbulence (e.g., due to COVID 19 crisis) or lack of the necessary knowledge, strategy, and resources to embark on the sustainability journey (Virmani et al., 2020).

Sustainable manufacturing is elusive and hard to define, as the literature has conceptualized and analyzed it from various perspectives depending on its purpose, dimensions, and application (Moldavska and Welo, 2017). Nonetheless, the economy, environment, and social dimensions, often labeled as the Triple Bottom Line (TBL), are the most widely accepted dimensions of sustainable manufacturing among industrial and academic communities (Junior et al., 2018). Sustainable manufacturing concerns the product life-cycle in its entirety, starting

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from the initial ideation to the entire manufacturing process until the end-of-life stage (Kamble et al., 2020). It requires a certain degree of integration and collaboration, scenario planning, and process innovation at the value chain scale, explaining the overall low adoption rate of sustainable manufacturing initiatives (Bhatt et al., 2020). Under such circumstances, Industry 4.0 technologies may offer exciting opportunities for addressing the TBL challenges of sustainable manufacturing at the factory and value chain levels. From an economic development point of view, Industry 4.0 and underlying digital technologies such as cyber-physical systems and the industrial internet of things are expected to decrease the operational costs involved in various manufacturing activities (Gouda and Saranga, 2020; Ngu et al., 2020). Industry 4.0 is also expected to contribute to the environmental dimension of manufacturing sustainability by reducing waste across value creation activities and promoting cleaner energy and material resources (Machado et al., 2020). Regarding the social sustainability dimensions, Industry 4.0 is believed to improve the working conditions and customer experience and create new job opportunities (Sartal et al., 2020). Despite these speculations, the literature struggles with answering the question of "*how can Industry 4.0 and the underlying digital industrial transformation contribute to sustainable manufacturing?*" (Sharma et al., 2020). The limited understanding of Industry 4.0 manufacturing sustainability functions is indeed expected, given that Industry 4.0-sustainability literature is in its early stages. The literature review reveals that only a handful of studies have empirically explained Industry 4.0 applications for sustainable manufacturing (Sharma et al., 2020). For example, Ghobakhloo and Fathi (2020) showed that Industry 4.0 technologies such as industrial automation and the internet of things contribute to manufacturing-economic sustainability by improving product quality and reducing defect rates. Strandhagen et al. (2020) empirically demonstrated how some Industry 4.0 technologies such as additive manufacturing could address the design barriers for sustainable ship production.

Nonetheless, Industry 4.0 boundaries extend far beyond the industrial application of stand-alone digital technologies such as additive manufacturing or augmented reality (Beier et al., 2020). To address the existing knowledge gap surrounding Industry 4.0 applications for sustainable manufacturing, the present study attempts to transmute the piecemeal evidence available within the literature into a strategic roadmap explaining the process through which Industry 4.0 enables sustainable manufacturing. To this purpose, the study first performs a systemic literature review to identify various Industry 4.0 manufacturing sustainability functions. Interpretive Structural Modeling (ISM) is further applied to establish interrelationships among various sustainability functions. Using ISM, the study structures empirical evidence available within literature and experts' opinions into a meaningful hierarchical model that explains how Industry 4.0 technologies can contribute to the TBL of sustainable manufacturing.

2. Sustainable manufacturing

Sustainable manufacturing is defined as a system of techniques, strategies, and activities to produce manufactured goods via economically sound value creation processes that aim to minimize adverse environmental impact, conserve energy and natural resources, and value stakeholders' (employees, consumers, and communities) welfare and safety (Garetti and Taisch, 2012; Machado et al., 2020; Sharma et al., 2020). Sustainable manufacturing involves making manufacturing processes more sustainable and developing more sustainable products to deliver the intended economic, environmental, and social benefits (Yong et al., 2020). Consistently, sustainable manufacturing holds a holistic view of the entire product life cycle and whole value creation and delivery channels to contribute to the TBL of sustainability (Kamble et al., 2020). The economic-manufacturing sustainability pillar denotes that manufacturers should operate profitably to pursue other sustainability goals (Ndubisi et al., 2020). However, this pillar does not follow the *profit at any cost* path, as it also values consumers and value partners' interests. The manufacturing-environmental sustainability pillar mainly concerns reducing the overall negative impact of manufacturing operations on the environment, mostly in the form of reducing carbon footprint, harmful emission, energy use, and waste (Le Bourhis et al., 2013). The manufacturing-social sustainability pillar is the most poorly defined and least acknowledged aspect of manufacturing sustainability, which concerns the stakeholders' well-being and the community in which a manufacturing value chain operates (Ghobakhloo et al., 2021). Improving customer experience, creating a better working environment, and creating fair employment opportunities are the most acknowledged aspects of manufacturing-social sustainability (Longoni and Cagliano, 2015). Nonetheless, this pillar may very well involve many micro-social concerns such as child labor or fair wage issues at any end of the supply network at the global scale (Mani et al., 2018; Sutherland et al., 2016).

Overall, companies incur higher costs due to deploying sustainability initiatives in the short-run (Mao and Wang, 2019). Nevertheless, manufacturers are increasingly pursuing sustainability in response to competitiveness and regulatory constraints (Machado et al., 2020). When planned strategically and implemented successfully, sustainable manufacturing initiatives can provide manufacturers with many advantages (Sartal et al., 2020). Cost-saving due to material, energy, and resource efficiency is the most evident benefit of sustainability, while brand reputation, public trust, and competitiveness are among the hard-to-quantify opportunities that sustainability efforts may deliver to manufacturers (Ngu et al., 2020). The Social and socio-economic Life Cycle Assessment (S-LCA) guideline developed under the United Nations Environment Programme offers a valuable technique for addressing the ambiguity surrounding the social sustainability concept. S-LCA offers a detailed guideline to internal and external stakeholders to effectively assess and map the social and socio-economic impacts of the product life cycle (UNEP, 2009).

Experts believe that sustainable manufacturing is the next evolutionary step after green manufacturing, rooted in the lean manufacturing philosophy (Kishawy et al., 2018). Contrary to lean manufacturing that merely values removing any non-value-added activity for the sole purpose of economic productivity, green manufacturing also values environmental conservation at the expense of lower productivity (Inman and Green, 2018). Sustainable manufacturing takes green manufacturing to the next level by holding the time perspective and valuing the impending sustainability implication of current manufacturing activities for future generations (Moldavska and Welo, 2017). Sustainable manufacturing nowadays is regarded as a dynamic transition process, given that its underlying elements, values, tools, and methods evolve continuously (Yong et al., 2020). Recent studies consistently strive to develop roadmaps for facilitating the implementation of innovative sustainable manufacturing practices (Kumar et al., 2020) and further understand how modern technologies such as additive manufacturing or blockchain contribute to sustainable thinking and development across manufacturing chains (Esmaeilian et al., 2020; Leng et al., 2020).

3. Industry 4.0 background

Industry 4.0 denotes the ongoing industrial revolution involving the digital transformation of value creation processes across various industries, including manufacturing. Industry 4.0 has evolved from the 'Industrie 4.0' vision, an initiative for increasing Germany's manufacturing industry competitiveness (Xu and Duan, 2019). The scope of Industry 4.0 was initially restricted to the digitalization of production processes at the factory level (Barata et al., 2020). Even so, the most recent literature holds a value chain-oriented perspective while defining the scope of Industry 4.0 (Benitez et al., 2020). Consistently, it is necessary to hold a holistic view of the industrial value chains, including suppliers of the materials and components, focal smart factories, distribution channels, and even smart customers when defining the scope of Industry 4.0 (Ardito et al., 2019; Dev et al., 2020a). Given the vagueness surrounding the concept of Industry 4.0, literature inclines to define it in terms of a reference architecture for digital transformation composed of two building blocks, namely *design principles* and *technology trends* (Culot et al., 2020).

Design principles of Industry 4.0 are a collection of necessary conditions that enable the digital industrial transformation to deliver its unique advantages. There are diverse perspectives on design principles of Industry 4.0, yet, real-time capability, virtualization, interoperability, decentralization, and virtual/horizontal integration are the most widely acknowledged design principles within the literature (Gilchrist, 2016). Technology trends of Industry 4.0 refer to a wide variety of information, digital, operations, and advanced manufacturing technologies that, collectively, push the digital industrial revolution (Zheng et al., 2021). Technology trends of Industry 4.0 can be classified into two categories of facilitating technologies and core technologies based on their functionality (Frank et al., 2019). Facilitating technologies include mature and widely accessible technologies that enable the implementation, integration, and proper operation of core technologies. Legacy networking infrastructure, software, computer-aided design and manufacturing tools, and sensors are examples of facilitating technologies (Muscio and Ciffolilli, 2020). Alternatively, core technologies are overhyped and recently commercialized digital technologies that enable the utmost level of flexibility, integrability, and automation. Cyber-physical systems, industrial internet of things, internet of data, additive manufacturing, artificial intelligence, predictive/prescriptive analytics, and cloud computing are examples of the core technology trends of Industry 4.0 (Lu, 2017).

Although young, Industry 4.0 literature has rich content, and the number of academic contributions to this discipline is growing exponentially (Oztemel and Gursev, 2020). Prior studies have made valuable contributions to the current understanding of the Industry 4.0 concept, scope, building blocks, implications, and ongoing trends (Culot et al., 2020). The sustainability implication of the digital industrial transformation is becoming one of the most popular research streams within the Industry 4.0 community (Beier et al., 2020). Industry 4.0 contribution to the circular economy (Kumar et al., 2021) and sustainable supply chain and logistics (Ding, 2018; Yadav et al., 2020) have been, respectively, the most popular streams of research within the Industry 4.0-sustainability literature. Surprisingly, the empirical assessment of Industry 4.0 implications for manufacturing sustainability is worryingly understudied (Machado et al., 2020). The literature is still struggling with understanding how manufacturers can implement the digital technologies of Industry 4.0 and align with the underlying digital transformation (Sharma et al., 2020), meaning there is limited empirical evidence on how the collective implementation of Industry 4.0 technologies and subsequently the development of underlying design principles have contributed to the various aspects of manufacturing sustainability.

4. Systematic literature review

The present study performs a Systematic Literature Review (SLR) to gain an objective summary of the Industry 4.0 contribution to sustainable development and identify the manufacturing sustainability functions of Industry 4.0. The study follows SLR guidelines (Tranfield et al., 2003) and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocols (PRISMA, 2020) to ensure the robustness of SLR and reliability of outcomes.

4.1. Resource identification

Fig. 1 provides an overview of the PRISMA-based flow chart reporting various SLR phases, including eligibility criteria and search strings. As explained in Fig. 1, the search string in this study consisted of six ‘Industry 4.0-related keywords’ AND eight ‘sustainability-related keywords.’ Step 1a of the SLR involved using the following search string for identifying the initial pool of articles within the *Scopus* database.

> Search String: (TITLE (“Industrie 4.0”) OR TITLE (“Industry 4.0”) OR TITLE (“Fourth industrial revolution”) OR TITLE (“Smart manufacturing”) OR TITLE (“Industrial internet”) OR TITLE (“Cyber physical system”) AND TITLE-ABS-KEY (“Sustainable manufacturing”) OR TITLE-ABS-KEY (“Sustainable production”) OR TITLE-ABS-KEY (“Green manufacturing”) OR TITLE-ABS-KEY (“Green production”) OR TITLE-ABS-KEY (“Manufacturing sustainability”) OR TITLE-ABS-KEY (“Production sustainability”) OR TITLE-ABS-KEY (“Sustainable operation”) OR TITLE-ABS-KEY (“Green operation"))

The literature widely acknowledges that Industry 4.0 is a complex and multifaceted phenomenon. To address the vagueness surrounding this phenomenon, scholars commonly define Industry 4.0 based on its major components, within which cyber-physical systems and smart manufacturing have been commonly considered major building blocks of Industry 4.0 (Zheng et al., 2021). Therefore, the SLR within the present study considered these two terms as major proxies of Industry 4.0 to ensure that no potentially important papers are ignored.

Step 1a of SLR was conducted in early November 2020, which resulted in identifying 129 documents. Stage 1b involved subjecting the initial pool of articles to five exclusion criteria listed in Fig. 1. Across stage 1b, 108 ineligible articles were removed, and 21 articles were shortlisted as the initial pool of eligible articles. Step 2a of SLR involved the backward review of eligible journal articles within which the reference section of articles shortlisted in step 1b was analyzed manually. This process led to identifying 1083 documents, out of which, and during the initial screening, 31 documents were classified as related documents not identified in step 1a. In step 2b, documents identified in step 2a were subjected to the exclusion criteria, which resulted in removing 24 documents and shortlisting seven additional documents as eligible articles. In step 3a, the forward review of 28 eligible journal articles (the updated pool of eligible journal articles in Fig. 1) was conducted, which involved using Google Scholar and Web of Science services for identifying documents that (1) cite the eligible articles shortlisted through steps 1b and 2b, (2) include at least one of the search string combinations, and (3) had not been previously shortlisted across steps 1a and 2a. During step 3a and out of 1418 citing documents, 43 new documents worthy of further investigation were identified. Across step 3b, the 43 articles identified in step 3a were subjected to the exclusion criteria, and as a result, 39 ineligible articles were removed, and four additional eligible articles were shortlisted. Overall, SLR and the underlying steps listed in Fig. 1 led to the final pool of 32 eligible articles.

4.2. Industry 4.0 manufacturing sustainability functions

In step 4 of the SLR and following the generally accepted guidelines (e.g., Higgins et al., 2019), two investigators analyzed the content of each eligible article qualitatively. A comprehensive content analysis protocol was designed to standardize the review procedure and enable investigators to avoid any rater bias, which explicitly described the extractable record types and coding scheme along with the denoising, data retrieval, and archiving procedures. After conducting the qualitative assessment of eligible articles independently, investigators shared their findings across a series of meetings, crosslinked sustainability functions identified, and eventually reached a shared consensus. Consequently, the SLR implemented in the present study led to identifying 15 unique manufacturing sustainability functions for Industry 4.0. Table 1 shows the distribution of the 15 sustainability functions as identified within the eligible articles. It is vital to note that Industry 4.0 functions for sustainable manufacturing, described below, offer pathways to a more sustainable manufacturing ecosystem in different qualities.

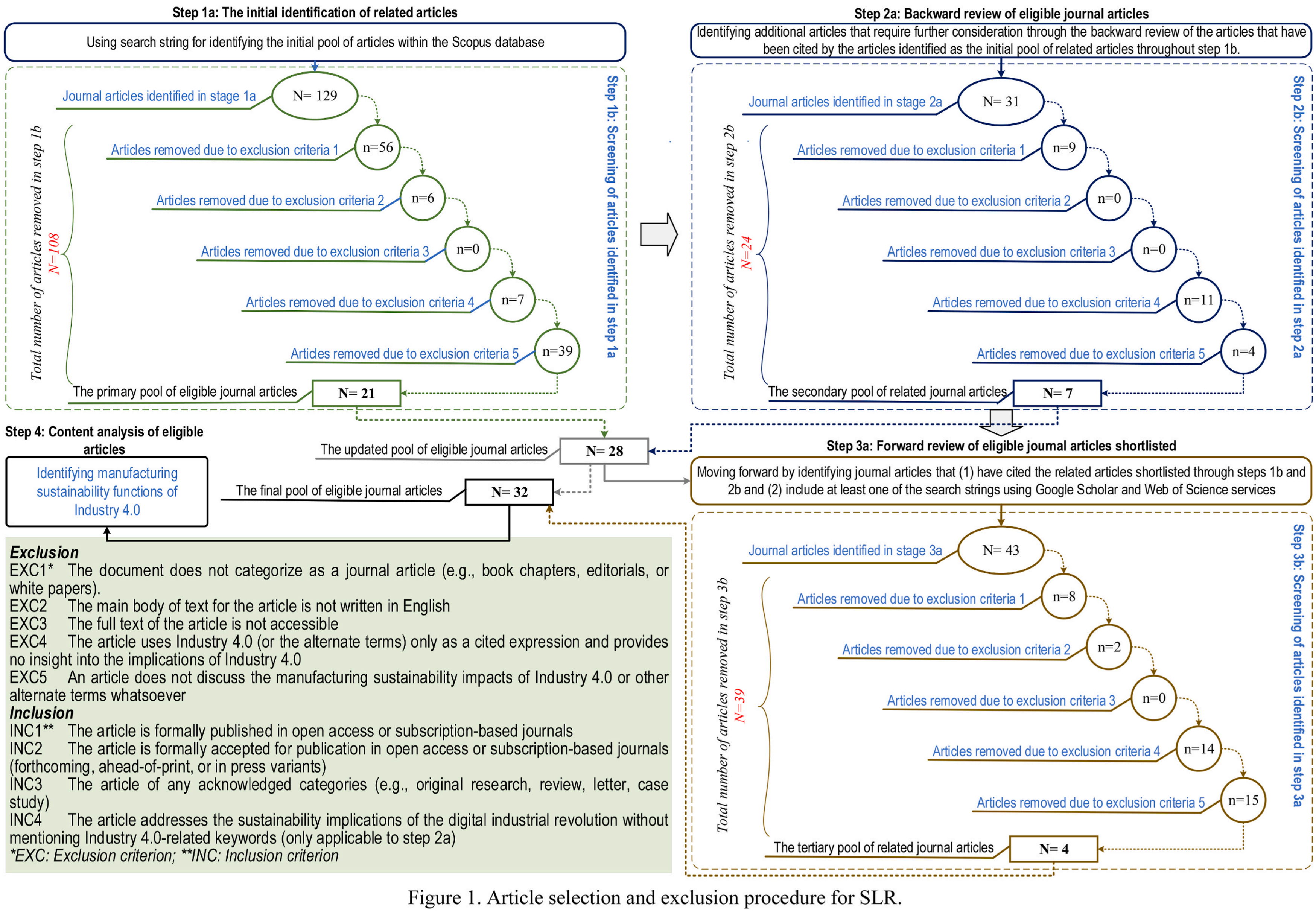

Fig. 1. Article selection and exclusion procedure for SLR.

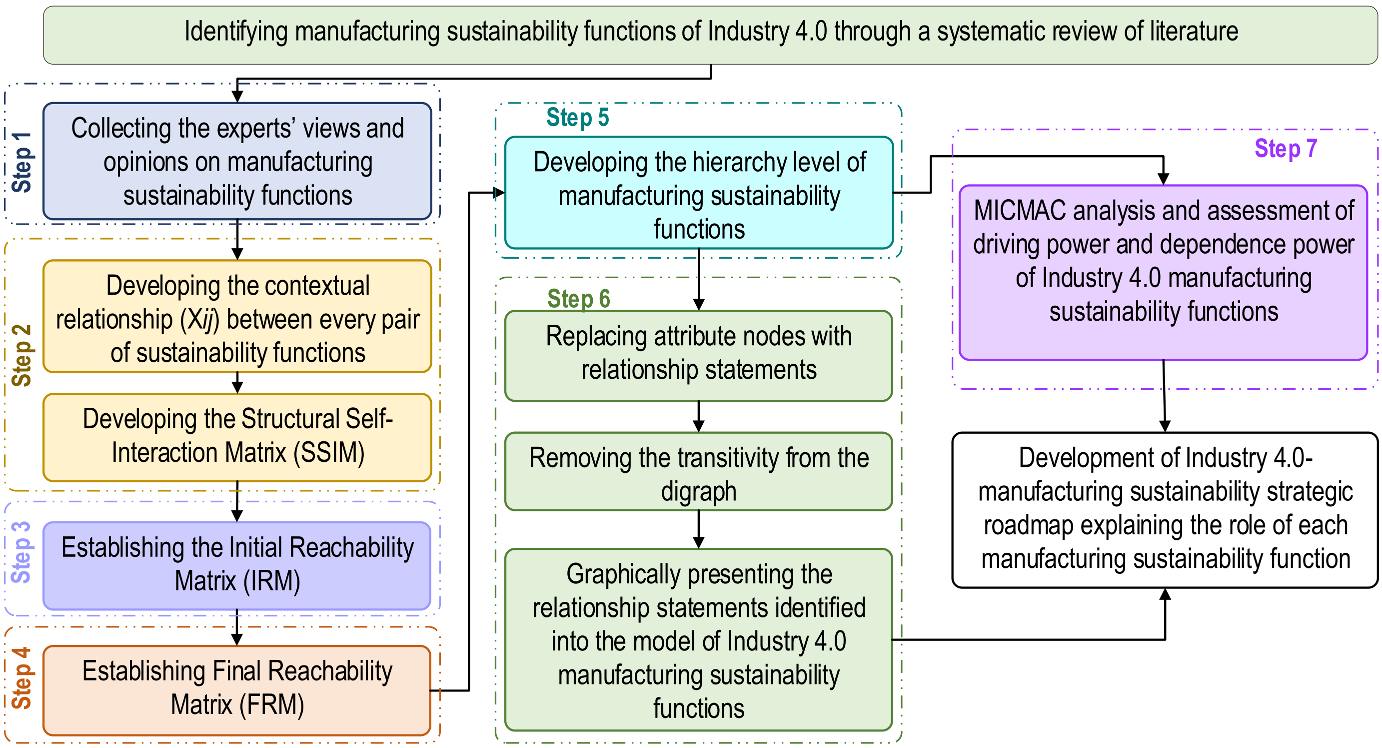

Fig. 2. ISM methodology and underlying steps applied.

Table 1
Results of content analysis of eligible articles.

No	Authors	BUMI	CUOM	EMPP	HAER	IMPM	IPPC	MANA	MAPE	NEEP	REEE	REMC	SSWE	SCPI	SUPD	SVCN
1	Bag et al. (2020)				x					x			x			
2	Beier et al. (2017)			x							x		x			
3	Bonilla et al. (2018)				x						x					
4	Braccini and Margherita (2019)				x			x	x			x	x	x	x	x
5	Dalenogare et al. (2018)							x	x				x			
6	de Sousa Jabbour et al. (2018)				x			x	x		x			x	x	
7	Ding (2018)					x			x					x		x
8	Esmaeilian et al. (2020)	x							x				x	x		
9	Fathi and Ghobakhloo (2020)						x				x					
10	Ford and Despeisse (2016)				x			x	x							
11	Ghobakhloo (2020)	x	x	x	x		x	x		x			x		x	x
12	Ghobakhloo and Fathi (2020)	x	x			x		x						x		
13	Gualtieri et al. (2020)												x			
14	Ivascu (2020)	x			x		x		x	x	x		x			x
15	Jena et al. (2020)				x				x		x					
16	Junior et al. (2018)				x								x			
17	Kamble et al. (2020)				x		x	x	x		x		x			
18	Kiel et al. (2017)	x		x	x	x		x		x		x	x		x	
19	Leng et al. (2020)	x	x		x					x	x			x	x	x
20	Li et al. (2020)	x					x				x			x		
21	Lim et al. (2021)					x	x		x			x				
22	Liu et al. (2019)			x									x			
23	Longo et al. (2017)			x									x			
24	Lopes de Sousa Jabbour et al. (2018)													x		x
25	Machado et al. (2020)		x	x		x		x		x		x			x	
26	Nascimento et al. (2019)								x		x					
27	Ren et al. (2019)										x					x
28	Sartal et al. (2020)				x						x		x		x	x
29	Strandhagen et al. (2020)			x	x	x	x	x			x	x	x	x		
30	Tsai (2018)						x		x		x	x				
31	Vrchota et al. (2020)			x	x	x			x			x	x			
32	Yadav et al. (2020)										x				x	x

Although the literature supplies necessary support for linking Industry 4.0 functions to various aspects of sustainable manufacturing, the sustainability benefits of these functions should not be taken for granted as they are dependent on the context and circumstances under which manufacturers operate. More importantly, these functions may not be unique for manufacturing systems with Industry 4.0 technologies. Industry 4.0 mostly delivers these functions through promoting and facilitating other tools, methods, and techniques for production and process improvements, examples of which include lean production or concurrent design and manufacturing. A brief description of each manufacturing sustainability function is provided in the following.

Business model innovation (BUMI): Industry 4.0 and its components, such as real-time capability, decentralization, or modularity, complemented by modern technologies such as additive manufacturing and internet of service, would allow manufacturers to revolutionize their operating model and value creation capability (García-Muiña et al., 2020; Li et al., 2020). In turn, business model innovation improves manufacturers' value proposition to customers by offering safer, cleaner, and more functional products and services (Leng et al., 2020).

Customer-oriented manufacturing (CUOM): Under Industry 4.0, technologies such as additive manufacturing, internet of service, internet of people, along with the modularity principle, enable manufacturers to develop a more agile and flexible manufacturing system that allows the personalization of products based on customer demands economically, in a way all stakeholders are provided with higher values (Wang et al., 2017).

Employee productivity (EMPP): Industry 4.0 and underlying real-time information sharing, clarity of communication, automation of tasks, interdepartmental connectivity, improved human-machine interaction, and streamlined production operations would increase employees' relative performance (Beier et al., 2017; Strandhagen et al., 2020). Higher employee productivity usually leads to healthier profit margins, improved working conditions, and a healthier business network (Jacobs et al., 2016).

Harmful emission reduction (HAER): Industry 4.0 enabling technologies and principles such as industrial internet of things, cyber-physical systems, intelligent robots, real-time capability, interoperability, and horizontal and vertical integration, and the emerging concepts such as smart factory and digital supply network offer tremendous opportunities for industrial efficiency and subsequently, emission control and reduction, and environmental preservation (Bag et al., 2020).

Improved manufacturing profit margin (IMPM): Smart factories under Industry 4.0 are more agile, flexible, and responsive (Yli-Ojanperä et al., 2019). Under the smart manufacturing environment, automated and efficient decision-making, higher product quality, more satisfied customers, and reduced business risk, along with many other advantages, provide manufacturers with an improved profit margin (Vrchota et al., 2020). In turn, economically productive manufacturers are better equipped to promote socio-environmental sustainability (Ghobakhloo and Fathi, 2020).

Intelligent production planning and control (IPPC): Industry 4.0 digital technologies such as industrial internet of things, artificial intelligence, big data, predictive analytics, and features such as data transparency, real-time information sharing, context-awareness capability, and the resulting process transparency facilitate the development of smart capabilities for production planning and control such as automated data collection or adaptive scheduling across shopfloor (Dev et al., 2020b). Optimized and intelligent production is a widely accepted facilitator of sustainable manufacturing (Fathi and Ghobakhloo, 2020).

Manufacturing agility (MANA): The integrative, decentralized, and interoperable manufacturing ecosystem under Industry 4.0 provides manufacturers with the necessary agility to efficiently cope with environmental uncertainties (Braccini and Margherita, 2019; Müller et al., 2018). Industry 4.0 also allows the manufacturing chain partners to promptly and cost-effectively apply the necessary product and process adjustment while optimizing the socio-environmental impacts of change processes employed (Kiel et al., 2017).

Manufacturing productivity and efficiency (MAPE): Industry 4.0 promotes the productivity and efficiency of manufacturing systems through technological development and improved connectivity (Jena et al., 2020). The resulting shopfloor automation, process monitoring, and supply chain visibility further lead to higher equipment reliability, reduced machine downtime, optimized inventory, and improved employee engagement (Ivascu, 2020), conditions that promote manufacturing profitability and environmental preservation (Jacobs et al., 2016).

New employment opportunities (NEEP): The digital transformation under Industry 4.0 increases the complexity of manufacturing systems tremendously (Bag et al., 2020). Despite the undeniable job loss to automation, Industry 4.0 creates new types of occupations that have not existed previously. Manufacturers investing in digital transformation have no choice but to add new professional profiles such as software engineers, information technology experts, and multiskilled machine operators to their workforce (Gualtieri et al., 2020). New employment opportunities under Industry 4.0, if governed correctly, can lead to reduced occupational and income inequality (Sung, 2018).

Resource and energy efficiency (REEE): Resource and energy efficiency is at the heart of Industry 4.0, given that the underlying innovative technologies provide real-time control over energy and resource consumption at the supply chain level (Bonilla et al., 2018). At the smart factory level, sensor-equipped machinery, machine controllers, the smart manufacturing execution system, and cloud-based energy management systems promote long-term sustainability by enabling continuous and real-time diagnosis of resource and energy consumption (Nascimento et al., 2019; Ren et al., 2019).

Reduced manufacturing costs (REMC): Industry 4.0 offers numerous manufacturing cost-saving opportunities such as autonomous 24/7 production, increased production volume, improved product quality, higher manufacturing precision, reduced manufacturing errors, and higher equipment effectiveness (Braccini and Margherita, 2019; Lim et al., 2021). Reduced manufacturing costs and resulting economic performance gain allow manufacturers to prioritize and better commit to socio-environmental development (Kamble et al., 2020).

Safe and smart working environment (SSWE): Industry 4.0 technologies such as Industry 4.0 and augmented reality lead to smarter and connected employees (Dalenogare et al., 2018). Smart wearables and augmented reality would allow in-context on-the-job training of employees to provide upskilling essential for maintaining safety and productivity in the industrial environment (van Lopik et al., 2020). Alternatively, automation and collaborative robots relieve workers of unergonomic and hazardous tasks (Taylor et al., 2020).

Supply chain process integration (SCPI): Horizontal integration and transformation of the traditional supply network into a digital and integrated entity are among the most fundamental design principles of Industry 4.0 (Esmaeilian et al., 2020). Integrative technologies such as the industrial internet of things, internet of services, internet of data, blockchain, and Cloud analytics enable the development of activity integration, real-time information sharing, physical flow integration, and financial flow integration capabilities across members of a supply chain (Strandhagen et al., 2020). Supply chain process integration and its features such as collaborative knowledge management, product development, product planning, demand planning, and decision-making initiatives offer massive economic and environmental development opportunities (Ding, 2018).

Sustainable product development (SUPD): Sustainable product development is hugely resource, information, and technology-intensive. Industry 4.0 supports SUPD by facilitating the life-cycle assessment approach to new product development (Leng et al., 2020). Digital twin technology and the simulation of a product's entire life cycle are revolutionizing the ideation phase of SUPD (Tao et al., 2018). Alternatively, high-performance computing computer-aided design and additive manufacturing technologies increase the effectiveness of the SUPD concept development phase (Dev et al., 2020b). More importantly, the smart manufacturing feature of Industry 4.0 promotes the SUPD product commercialization phase thanks to its efficiency and productivity capabilities (Lin, 2018).

Sustainable value-creation networking (SVCN): Co-creating sustainability across value chains requires all value chain members, from the lowest tier supplier to the end consumer, to embrace the concept of sustainability to co-create value (Kiel et al., 2017). Fortunately, Industry 4.0 and underlying technologies enable the integration of value chains so all value chain members can contribute to co-creating more sustainable products and services (Ardito et al., 2019). Besides, Industry 4.0 facilitates the incorporation of eco-friendly technologies, raw materials, and renewable energy sources across manufacturing chains and ensures that sustainable features are recognized across value chains, so the sustainability advantages are distributed impartially among all value chain members (Ivascu, 2020; Sartal et al., 2020).

5. Interpretive structural modeling methodology

ISM is a well-established technique for theory development as it helps scholars identify and establish interrelationships among specific factors that collectively define a system, which may involve a particular problem, issue, or phenomenon (Gardas et al., 2019). ISM excels in developing graphical representations of complex systems and translating unclear and vaguely articulated mental concepts into structured and meaningful hierarchical models (Singhal et al., 2019). ISM has been considerably popular within the sustainability discipline, widely used for modeling biomass sustainability (Azevedo et al., 2019), sustainable supply chain management (Hussain et al., 2016), collaborative green innovation (Yang and Lin, 2020), renewable energy implementation (Ansari et al., 2013), green lean implementation (Cherrafi et al., 2017), and green human resource management (Moktadir et al., 2019). Fig. 2 explains the steps taken within the present study for applying ISM, which follows the standard procedures widely accepted within the ISM literature (Ghobakhloo et al., 2021).

5.1. Collecting expert's opinion

ISM uses experts' opinions for identifying the contextual relationships among components of a system (Azevedo et al., 2019). The study followed rigorous expert selection and opinion mining procedures (e.g., Hertzum, 2014) to minimize the method bias and ensure the reliability and validity of outcomes. First, and in collaboration with several European universities and research centers, the research team identified a pool of 13 experts with a vast knowledge of Industry 4.0 digital transformation and manufacturing sustainability in terms of real-world industrial experience in leading European industries and distinguished academic contributions. The study further conducted the initial screening of experts, which involved a series of semi-structured interviews for assessing the willingness, availability, and knowledgeableness of experts. Consistently, seven experts shortlisted contributed to this study by participating in a series of Nominal Group Technique (NGT)-based online meetings (via Zoom). NGT is a reliable method of collaborative knowledge sharing and decision-making, which is commonly used within ISM literature (Ghobakhloo, 2020). Experts' opinions were collected across five NGT-based meetings held in early December 2020. Experts assessed the validity of Industry 4.0 manufacturing sustainability functions identified across the first two meetings. Experts further identified and described the causal relationships between the functions during meetings 3, 4, and 5.

5.2. Establishing contextual relationships

Structural Self-Interaction Matrix (SSIM) is developed by applying a set of coding schemes to the relationships identified based on experts' opinions. Following the ISM methodology (Moktadir et al., 2019), the coding scheme in this study includes:

V: Manufacturing sustainability function *i* causes manufacturing sustainability function *j;*

A: Manufacturing sustainability function *i* is caused by manufacturing sustainability function *j;*

X: Manufacturing sustainability functions *i* and *j* cause each other;

O: Manufacturing sustainability functions *i* and *j* are causally independent.

The application of the coding scheme to experts' opinions resulted in the development of the SSIM of the study, as Table 2. For example, the SSIM explains that customer-oriented manufacturing and improved manufacturing profit margin mutually cause each other, given the CUOM-IMPM entry in Table 2 is presented by symbol X.

5.3. Establishing the initial reachability matrix

To establish the Initial Reachability Matrix (IRM), the SSIM is subjected to the following conversion rules widely acknowledged within the ISM discipline (Singhal et al., 2019):

If SSIM symbolizes *(i, j)* entry as V, then *(i, j)* and *(i, j) entries* in the IRM are, respectively, set to 1 and 0;

If SSIM symbolizes *(i, j)* entry as A, then *(i, j)* and *(i, j) entries* in the IRM are, respectively, set to 0 and 1;

If SSIM symbolizes *(i, j)* entry as X, then *(i, j)* and *(i, j) entries* in the IRM are both set to 1, and;

If SSIM symbolizes *(i, j)* entry as O, then *(i, j)* and *(i, j) entries* in the IRM are both set to 0.

Consistently, the study followed the conversion rules and developed the IRM as Table 3.

5.4. Establishing the final reachability matrix

Final Reachability Matrix (FRM) is established by subjecting IRM to the transitivity rule, which accounts for indirect causality. The transitivity rule explains that when function A causes function B, and function B causes function C, function A is assumed to cause function C (Gardas et al., 2019; Cherrafi et al., 2017). Table 4 presents the FRM of the study, which includes the driving power and dependence power of each function. For a given function, driving power equals the number of functions directly or indirectly (based on transitivity) caused, whereas dependence power denotes the number of functions directly or indirectly caused by (Ghobakhloo et al., 2021).

5.5. Identifying the hierarchy level of functions

The hierarchy level of functions is identified by developing the reachability, antecedent, and intersection sets for each function and further executing iterative extraction procedures (Hussain et al., 2016). For a given function, the reachability set includes the function and other functions caused by it, whereas the antecedent set consists of the function and other functions that cause it (Gardas et al., 2019). The intersection for a given function includes functions commonly present in both reachability and antecedent sets (Ansari et al., 2013). To identify the hierarchy level of functions, extraction procedures are conducted iteratively so that in each iteration, functions with identical reachability and intersection sets are identified and extracted. Table A1 lists the hierarchal levels of Industry 4.0 sustainable manufacturing functions, within which harmful emission reduction (HAER) and new employment opportunities (NEEP) functions are extracted in iteration I. Overall, extracted functions in each iteration are removed across the reachability, antecedent, and intersection sets in the subsequent iterations. The extraction procedure is repeated iteratively to identify the hierarchy level of all functions. Table A1 explains that the hierarchy levels of Industry 4.0 manufacturing sustainability functions are identified across nine iterations.

Table 2
The structural self-interaction matrix.

Factors	SVCN	SUPD	SCPI	SSWE	REMC	REEE	NEEP	MAPE	MANA	IPPC	IMPM	HAER	EMPP	CUOM	BUMI
BUMI	O	O	A	O	O	V	V	V	V	O	V	O	O	V	–
CUOM	O	V	A	O	A	O	O	O	A	A	X	O	O	–	
EMPP	O	O	O	A	V	V	O	V	V	X	V	O	–		
HAER	A	O	O	O	O	A	O	A	O	O	O	–			
IMPM	V	V	A	O	A	A	V	A	A	O	–				
IPPC	O	O	A	O	O	O	O	V	V	–					
MANA	O	O	A	O	V	O	O	X	–						
MAPE	O	O	A	A	V	V	O	–							
NEEP	A	A	O	O	O	O	–								
REEE	O	A	O	O	V	–									
REMC	O	O	O	O	–										
SSWE	O	O	O	–											
SCPI	V	V	–												
SUPD	A	–													
SVCN	–														

Table 3
The initial reachability matrix.

Factors	BUMI	CUOM	EMPP	HAER	IMPM	IPPC	MANA	MAPE	NEEP	REEE	REMC	SSWE	SCPI	SUPD	SVCN
BUMI	1	1	0	0	1	0	1	1	1	1	0	0	0	0	0
CUOM	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0
EMPP	0	0	1	0	1	1	1	1	0	1	1	0	0	0	0
HAER	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
IMPM	0	1	0	0	1	0	0	0	1	0	0	0	0	1	1
IPPC	0	1	1	0	0	1	1	1	0	0	0	0	0	0	0
MANA	0	1	0	0	1	0	1	1	0	0	1	0	0	0	0
MAPE	0	0	0	1	1	0	1	1	0	1	1	0	0	0	0
NEEP	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
REEE	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0
REMC	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0
SSWE	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0
SCPI	1	1	0	0	1	1	1	1	0	0	0	0	1	1	1
SUPD	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0
SVCN	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1

5.6. Structuring the interpretive model

Fig. 3 presents the ISM model of Industry 4.0 manufacturing sustainability functions. This model has been developed based on the hierarchal levels identified in Table A1 and representing the causal relationships identified with vector arrows. Consistent with Table A1, the 15 sustainability functions have been placed across nine placement levels within the ISM model but in reverse order, meaning functions extracted at the last iteration have been positioned in the first placement level within the model. Consistent with the ISM standard procedures (Warfield, 1982), only the direct relationships between functions of consecutive placement levels are illustrated graphically by vector arrows.

According to Fig. 3, Industry 4.0 primarily promotes the manufacturing-economic productivity pillar of sustainable manufacturing, particularly through the sustainability functions placed as placements levels 1 to 3. For this purpose, Industry 4.0 first delivers the supply chain process integration function by drawing on its core design principles of *vertical* and *horizontal integration*. Under the Industry 4.0 agenda, through the vertical integration of smart manufacturing systems, Industry 4.0 offers the utmost level of control, monitoring, and data integration across various functions of manufacturing units. Alternatively, the horizontal integration principle of Industry 4.0 allows the creation of a hyper-connected global manufacturing value chain that features integrated transparency, flexibility, and constant traceability. On the other hand, Industry 4.0 delivers the 'safe and smart working environment' function thanks to its *technical assistance* principle that involves using Cyber-Physical Systems (CPS) to empower and support human labor through automating unsafe and unpleasant industrial tasks as well as collecting and visualizing a large volume of data for supporting informed decision making. Through these two functions, Industry 4.0 further enables three functions of business model innovation, employee productivity, and intelligent production planning and control, both at the corporate and value chain levels. At the smart factory level of Industry 4.0, enabling technologies such as Industrial Internet of Things (IIoT), CPS, and big data analytics, and operations technologies such as industrial control systems and autonomous robots streamline and automize countless functions related to the management of production and organization, such as maintenance management, materials and part tracking, monitoring of quality fluctuations, and availability of resources. At the supply chain level, networking of business partners via Industry 4.0 technologies such as IIoT, cloud technologies, and blockchain ensure the traceability, transparency, and flexibility of the entire supply chain processes, from inbound logistics to outbound logistics. Because of these features, manufacturers can enjoy higher operational and employee productivity and consider adopting new business models such as cloud manufacturing or the product-as-a-service model.

Industry 4.0 sustainability functions positioned in placement levels 1 and 2 further facilitate the two functions of manufacturing agility and manufacturing productivity and efficiency. Industry 4.0 contributions to manufacturing agility and efficiency involve using exponential technologies such as Artificial Intelligence (AI), additive manufacturing, and digital twin and applying key design principles of decentralization, interoperability, and modularity. Under the Industry 4.0 agenda, the decentralization principle involves incorporating decentralized intelligence into integrated manufacturing and business processes to reduce the complexity of operations. The interoperability principle of Industry 4.0 ensures the reliable and meaningful communication of manufacturing micro components such as operators, machines,

Table 4
Final reachability matrix for Industry 4.0 sustainable manufacturing functions.

Factors	BUMI	CUOM	EMPP	HAER	IMPM	IPPC	MANA	MAPE	NEEP	REEE	REMC	SSWE	SCPI	SUPD	SVCN	Driving power	*Rank*
BUMI	1	1	0	1*	1	0	1	1	1	1	1*	0	0	1*	1*	**11**	*3*
CUOM	0	1	0	0	1	0	0	0	1*	1*	0	0	0	1	1*	**6**	*8*
EMPP	0	1*	1	1*	1	1	1	1	1*	1	1	0	0	1*	1*	**12**	*2*
HAER	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**1**	*10*
IMPM	0	1	0	1*	1	0	0	0	1	1*	0	0	0	1	1	**7**	*7*
IPPC	0	1	1	1*	1*	1	1	1	0	1*	1*	0	0	1*	0	**10**	*4*
MANA	0	1	0	1*	1	0	1	1	1*	1*	1	0	0	1*	1*	**10**	*4*
MAPE	0	1*	0	1	1	0	1	1	1*	1	1	0	0	1*	1*	**10**	*4*
NEEP	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	*10*
REEE	0	1*	0	1	1	0	0	0	1*	1	1	0	0	1*	1*	**8**	*6*
REMC	0	1	0	0	1	0	0	0	1*	0	1	0	0	1*	1*	**6**	*8*
SSWE	0	0	1	1*	1*	1*	1*	1	0	1*	1*	1	0	0	0	**9**	*5*
SCPI	1	1	1*	1*	1	1	1	1	1*	1*	1*	0	1	1	1	**14**	*1*
SUPD	0	0	0	1*	1*	0	0	0	1	1	1*	0	0	1	0	**6**	*8*
SVCN	0	0	0	1	0	0	0	0	1	1*	0	0	0	1	1	**5**	*9*
Dependence power	**2**	**10**	**4**	**12**	**12**	**4**	**7**	**7**	**12**	**12**	**10**	**1**	**1**	**12**	**10**		
Rank	*5*	*2*	*4*	*1*	*1*	*4*	*3*	*3*	*1*	*1*	*2*	*6*	*6*	*1*	*2*		

processes, and equipment across different business functions and all along the value chain. Under the modularity principle, Industry 4.0 ensures that complex value chains and their components, such as smart factories and delivery networks, have the required physical and managerial flexibility to deal with environmental turbulence. When combined with AI, IIoT, CPS, robots, and embedded and control systems, these principles result in unparalleled agility of manufacturing systems and improvement of production efficiency (e.g., in terms of operations effectiveness, defect rate, and production downtime). Overall, Fig. 3 shows that by enabling functions at placement levels 1 to 3, which primarily enable the production-economic pillar of sustainable manufacturing at corporate and supply chain levels, Industry 4.0 unlocks essential functions for the environmental pillar of sustainable manufacturing.

Industry 4.0 particularly delivers the resource and energy efficiency function by improving the methods of production, facilitating the implementation and integration of more energy and resource-efficient production and operations technologies, and simplifying the integration of renewables into industrial operations. Moreover, the technological constituents of Industry 4.0, such as AI, smart sensors, and cloud computing, promote energy management by enabling the real-time monitoring of micro energy systems across various manufacturing operations. Consistently, the sustainability functions of Industry 4.0 positioned in placement levels 1 to 4, collectively, reduce manufacturing costs (the REMC function) and improve the profit margin of manufacturing operations. Besides improving employee productivity, workplace safety, and energy/material efficiency, Industry 4.0 improves manufacturing cost efficiency and profit margin by supporting and empowering various manufacturing cost minimization techniques. In doing so, Industry 4.0 and the underlying autonomy streamline order fulfillment, improve collaboration and relationships with suppliers, increase the efficiency of various manufacturing-management practices (e.g., lean production or six sigma), promote the economies of scale, reduce the defect rate, and improve the overall quality of products and services. Similarly, the previously mentioned functions of Industry 4.0 enable manufacturers to collaborate with customers closely and have the necessary capacity, agility, and flexibility to produce only what customers truly desire.

By unlocking and delivering sustainability functions positioned in placement levels 1 to 6 of Fig. 3, Industry 4.0 enables manufacturing chains to practically contribute to the socio-environmental pillar of sustainable manufacturing without critically sacrificing revenue and competitiveness. The horizontal integration and real-time communication principles of Industry 4.0, along with cloud data technology, enable value chain partners to communicate and share information and knowledge securely. Therefore, Industry 4.0 allows manufacturing partners to build the essential trust and mobilize the necessary resources to address some of the major socio-environmental sustainability concerns proactively. In particular, Industry 4.0 sustainability functions (in placement levels 1 to 6) allow all value chain members to collaborate on involving the internal and external stakeholders and introduce sustainable innovation into product design, development, and production processes and achieve the key functions of sustainable value-creation networking and sustainable product development. By doing so, the digitalization of manufacturing value chains under the Industry 4.0 agenda serves society by creating new employment opportunities in various areas such as software engineering, applications engineering, renewable energy engineering, data analytics, and industrial symbiosis. It further serves environmental sustainability by reducing harmful emissions, especially thanks to the integration of renewables, eco-design engineering, reducing yield losses, and end-of-life management.

5.7. MICMAC analysis

Cross-impact matrix multiplication applied to classification, commonly referred to as MICMAC (Matrices d'Impacts Croises

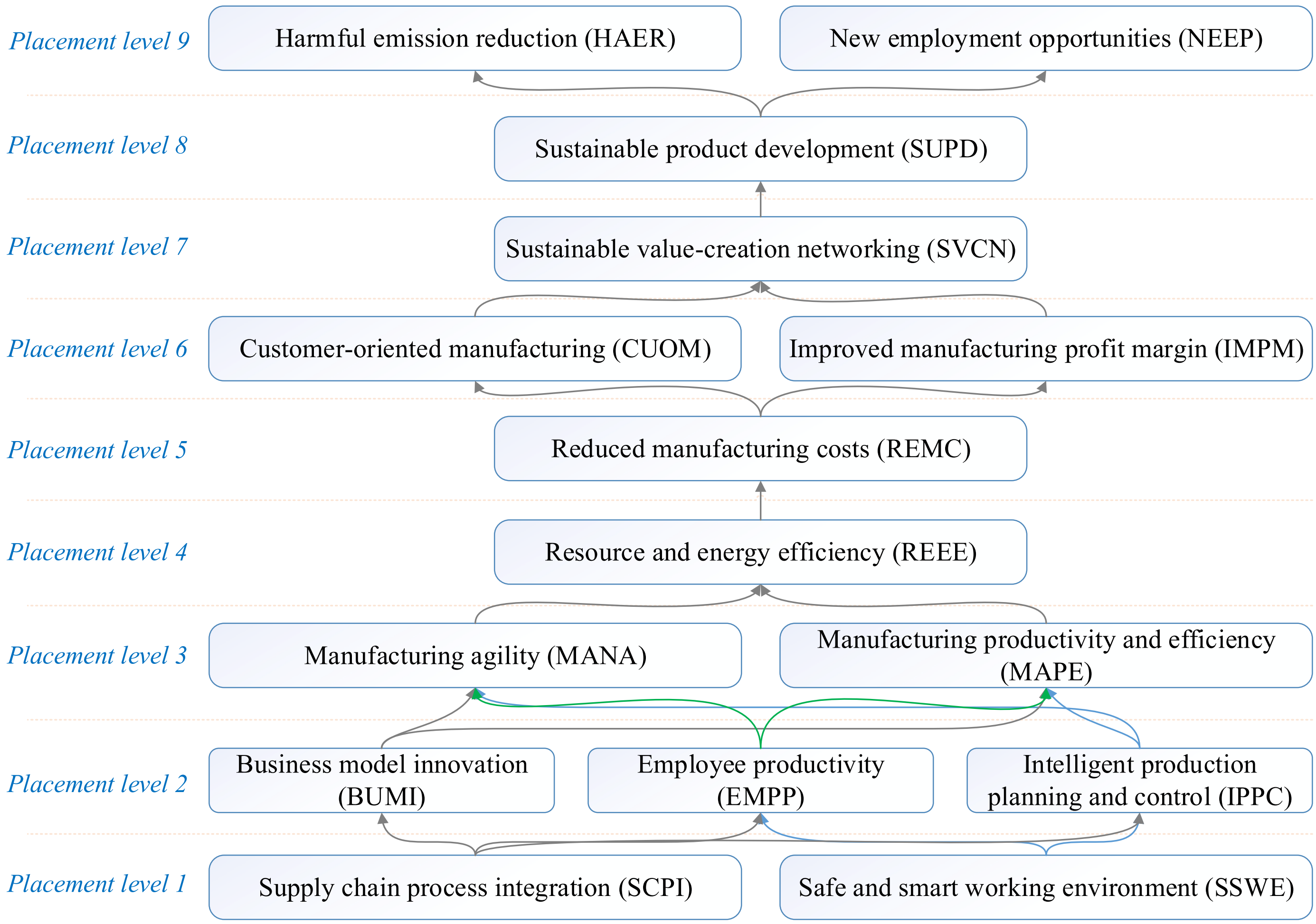

Fig. 3. ISM model of Industry 4.0 manufacturing sustainability functions.

Multiplication Appliqué an un Classement) analysis complements ISM by classifying components of a system based on their deriving power and dependence power (Singhal et al., 2019). MICMAC classifies system components into four clusters, resulting in a cartesian coordinate system with autonomous, driver, linkage, and dependent quadrants (Yang and Lin, 2020). Functions with weak driving and dependence power are placed in autonomous quadrants. The driver quadrant consists of functions with strong driving power but weak dependence power. Functions with strong driving power and dependence power are placed in the *linkage* quadrant. Lastly, the dependence quadrant includes functions with weak driving power but strong dependence power. Fig. 4 presents the results of MICMAC analysis regarding the manufacturing sustainability functions of Industry 4.0.

6. Discussion

The SLR identified 15 manufacturing sustainability functions of Industry 4.0, and the ISM model presented in Fig. 3 revealed that these functions are partitioned into nine placement levels. Overall, ISM results indicate that the mechanism through which Industry 4.0 may contribute to sustainable manufacturing is considerably complicated, involving the favorable presence of various interdependent functions with diverse driving and dependence power. Fig. 3 explains that supply chain process integration and a safe and smart working environment are the most immediate and fundamental opportunities that Industry 4.0 offers for sustainable manufacturing, facilitating placement level 2 functions of business model innovation, employee productivity, and intelligent production planning and control. Placement level 2 functions further

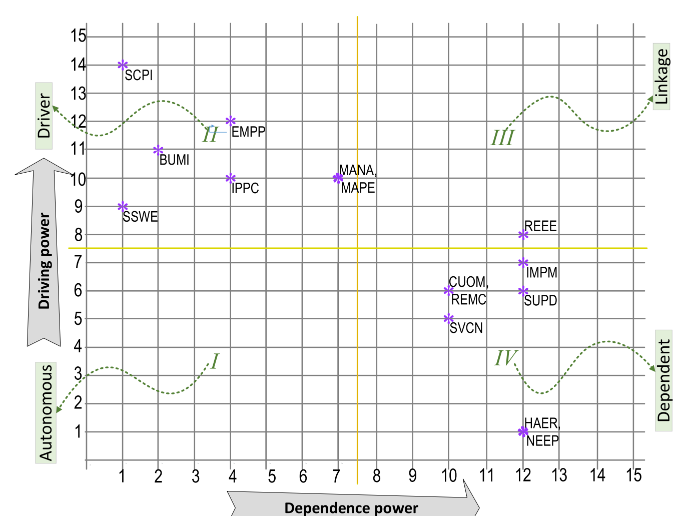

Fig. 4. Driving and dependence power matrix.

enable manufacturing agility and manufacturing productivity and efficiency. The seven functions positioned across placement levels 1 to 3 in Fig. 3 are classified as *driver* functions (Fig. 4), meaning they play a vital role in enabling more dependent sustainability functions. Resource and energy efficiency, positioned in the placement level 4 in Fig. 3, is the only *linkage* function within MICMAC analysis (Fig. 4). Resource and energy efficiency facilitates reduced manufacturing cost function, which is the most iconic manufacturing-economic sustainability measure. Reduced manufacturing cost function further leads to customer-oriented manufacturing and improved manufacturing profit margin that, in turn, facilitate the development of sustainable value-creation networking and, consequently, sustainable product development function. Finally, harmful emission reduction and new employment opportunities functions are positioned at placement level 9. This result, complemented by the MICMAC analysis in Fig. 4, reveals that harmful emission reduction and new employment opportunities are the most remote and challenging opportunities that Industry 4.0 may offer for sustainable manufacturing, given that their development is highly dependent on the favorable presents of many other sustainability functions.

The ISM model developed in Fig. 3 merely shows the order through which Industry 4.0 sustainability functions realistically contribute to materializing sustainable manufacturing. Consistent with ISM rules, the model in Fig. 3 only depicts direct causal relationships between sustainability functions positioned at successive placement levels. Consistently, the study builds an interpretive logic-knowledge base according to the experts' opinions and develops the Industry 4.0-manufacturing sustainability roadmap as Fig. 5. To reduce the overall complexity of Fig. 5, the functionality of each causal relationship in this figure is described in the function role matrix presented in Table A2. This roadmap builds on the direct relationships identified within the IRM (Table 3) and follows the extraction patterns identified in Table A1 for each function placement order. The roadmap presented in Fig. 5 and Table A2 clearly describe each causal relationship among various sustainability functions. For example, Table A2 explains that the SCPI→SUPD relationship in Fig. 5 means *supply chain process integration* facilitates *sustainable new product development* by enabling sustainable process alignment and collaborative green research and development efforts across supply partners.

Figs. 3 and 5, collectively, reveal that Industry 4.0 contributes to manufacturing sustainability through a very complex procedure involving various highly interrelated functions. Supply chain process integration (SCPI) is arguably the most fundamental sustainability function of Industry 4.0, given it is the direct facilitator of eight sustainability functions of business model innovation (BUMI), customer-oriented manufacturing (CUOM), improved manufacturing profit margin (IMPM), intelligent production planning and control (IPPC), manufacturing agility (MANA), manufacturing productivity and efficiency (MAPE), sustainable value-creation networking (SVCN), and sustainable product development (SUPD). SCPI function enables other sustainability functions by streamlining various supply chain activities and promoting information sharing and transparency, conditions that promote cross-functional collaboration, sustainable partnership, value chain performance monitoring, and collaborative green product and process innovation. The safe and smart working environment (SSWE) function is the most fundamental socially-oriented sustainability function of Industry 4.0, holding a critical role in transferring the value of manufacturing digital transformation into sustainable development. SSWE function delivers its value by enabling employee productivity (EMPP) and MAPE functions in terms of promoting employee empowerment, the safety of the work environment, employees' sense of ownership, and informed decisions, to name a few.

The three functions of BUMI, EMPP, and IPPC positioned at the placement level 2 of Fig. 4 are essential organizational functions that play a critical *driving* role in delivering the sustainability value of Industry 4.0. In particular, BUMI, EMPP, and IPPC enable two manufacturing-economic sustainability functions of MANA and MAPE, mainly by introducing innovation into business operations, offering an agile operating model, improving equipment effectiveness, introducing lean practices, the flexibility of work schedules, and inventory optimization. At one placement level higher, EMPP, BUMI, and MAPE functions, collectively, enable the only *linkage* function of resource and energy efficiency (REEE), mainly through sustainable thinking, optimizing throughput, industrial symbioses, defect management strategies, maintenance management effectiveness, and improved reliability of production operations. As the only linkage function, REEE plays a critical role in enabling the *dependent* sustainability functions of Industry 4.0. In particular, REEE delivers its function by enabling reduced manufacturing costs (REMC function) and reducing per unit material and energy costs.

The REMC function further allows manufacturers to develop the customer-oriented manufacturing capability (CUOM function) and enjoy a more significant manufacturing profit margin (IMPM function). REMC function delivers these opportunities by enabling manufacturers to achieve higher product profit margins, gain the financial capacity to invest in reconfigurable manufacturing, implement product individualization strategy, and increase market penetration. The capability to integrate with supply partners (SCPI function) and optimize manufacturing profitability (IMPM function) further allows manufacturers to engage in sustainable value-creation networking (SVCN function). In particular, SCPI and IMPM functions enable SVCN by allowing manufacturers to actively access the necessary capital and operational alignment to engage in sustainability co-governance and sustainable value co-creation. In turn, the SVCN function, complemented by SCPI, IMPM, and CUOM, allows manufacturers to achieve sustainable product development capability (SUPD function). SVCN function delivers this enabling role by streamlining internal and external collaborations on green product ideation, green product innovation, and product eco-efficiency analysis. Alternatively, SCPI, IMPM, and CUOM enable SUPD through collaborative green R&D, supply chain alignment for product life cycle management, and customer integration for green product design.

Positioned at placement level 9, new employment opportunities (NEEP) and harmful emission reduction (HAER) are the most dependent and outlying functions of Industry 4.0 for sustainable manufacturing. As the direct enablers of NEEP, the four functions of BUMI, IMPM, SUPD, and SVCN lead to new employment opportunities in data analytics, problem-solving, green ideation, digital twinning, rapid prototyping, new product launch, technology development and implication, and product life-cycle management. Alternatively, MAPE, REEE, and SVCN functions directly enable the HAER function, mainly by energy and material consumption optimization, optimized material handling, resource recycling, incorporating cleaner resources and operations, and emission audits at the corporate and supply chain levels.

Overall, neither SCPI nor any other sole function can alone unlock the full sustainability potential of the digital industrial transformation. This level of complexity roots in the scope of Industry 4.0 that involves the digitalization of all value creation processes across various industries. Therefore, benefiting from manufacturing sustainability opportunities of Industry 4.0 requires meticulous planning, including stepwise development of each sustainability function based on their driving forces and dependence levels. Figs. 4 and 5 offer exciting insights into how Industry 4.0 contributes to the economic, environmental, and social aspects of sustainable manufacturing. As the more important environmental and social sustainability implications, harmful emission reduction and new employment opportunities are the least accessible opportunities that Industry 4.0 may offer. ISM results show that the manufacturing ecosystem should first enjoy the economic sustainability opportunities of Industry 4.0 to have the capacity to priorities social and environmental development. Fig. 5 further supports this finding by highlighting the critical enabling role of *improved manufacturing profit margin* in transferring the economic sustainability value of Industry 4.0 into the development of economically controversial functions such as sustainable product development and sustainable value-creation networking.

7. Conclusion, implications, and future direction

The present study attempted to address the knowledge gap

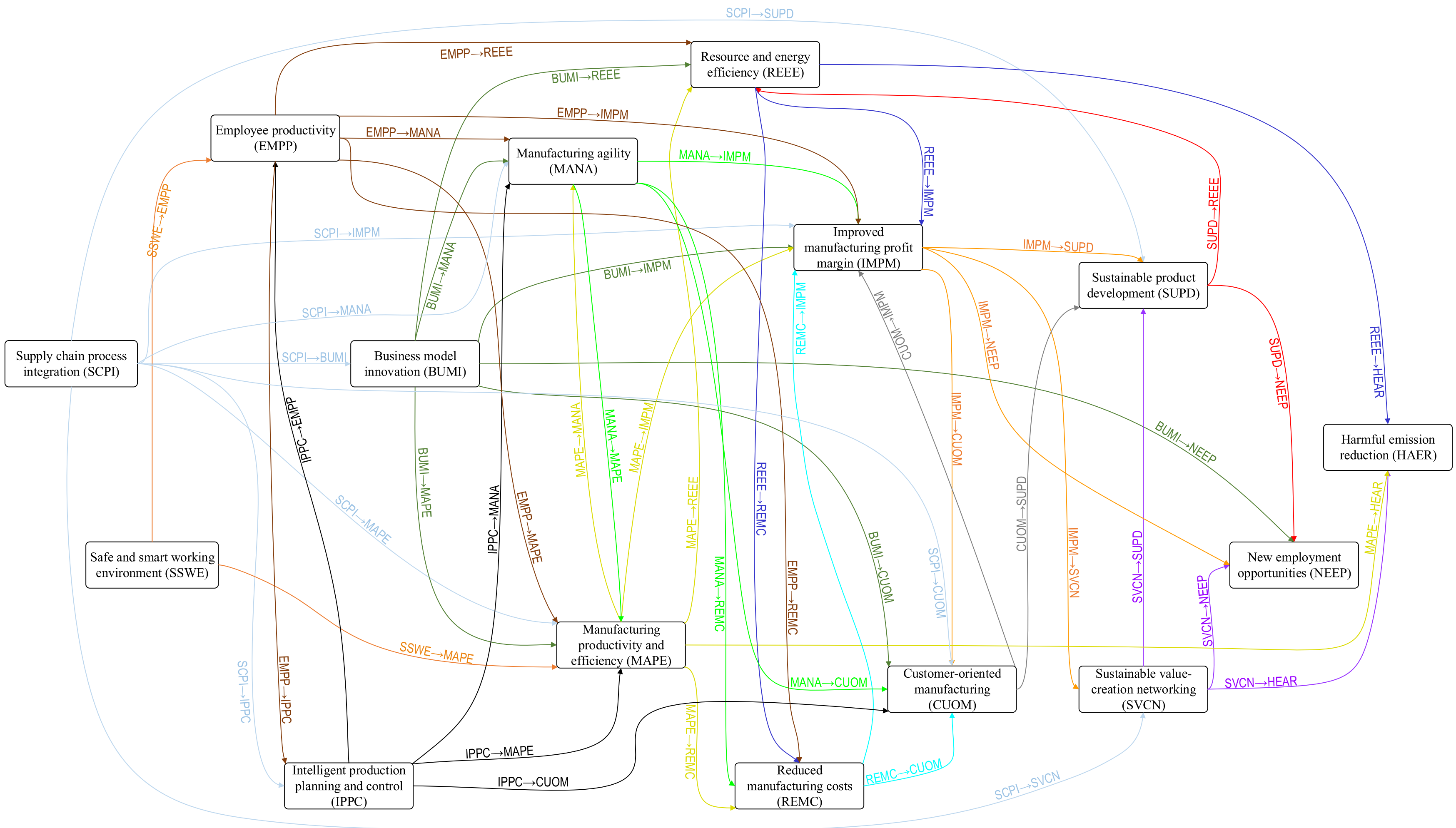

Fig. 5. Industry 4.0 contribution roadmap for sustainable manufacturing.

surrounding the opportunities that Industry 4.0 and the digital industrial revolution may offer for sustainable manufacturing. Findings showed that Industry 4.0 contributes to sustainable manufacturing through 15 highly interrelated functions, namely business model innovation, customer-oriented manufacturing, employee productivity, harmful emission reduction, improved manufacturing profit margin, intelligent production planning and control, manufacturing agility, manufacturing productivity and efficiency, new employment opportunities, resource and energy efficiency, reduced manufacturing costs, safe and smart working environment, supply chain process integration, sustainable product development, and sustainable value-creation networking. The role of each sustainability function was explained thoroughly within the sustainable manufacturing roadmap developed in the study. Overall, results show that Industry 4.0 can play a critical enabling role in sustainable manufacturing. The implications of the present research can be narrated as follow:

- Industry 4.0 and sustainable manufacturing share many common grounds that emphasize efficiency, productivity, continuous improvement, and better customer experience. Results showed that Industry 4.0 promotes sustainable manufacturing via a complicated, gradual, knowledge-base, and costly mechanism, requiring manufacturers to have a certain degree of technological and managerial readiness and maturity. Not all manufacturers may have the capability for Industry 4.0 digital transformation. Nonetheless, standalone Industry 4.0 technologies such as additive manufacturing or augmented reality can still contribute to some specific aspects of sustainable manufacturing.
- Industry 4.0 is a complex and multifaceted phenomenon involving many technologies and their applications in a hyper-connected manufacturing ecosystem. Each technology trend of Industry 4.0 offers unique sustainability implications. For example, additive manufacturing promotes sustainable manufacturing via offering end-of-life solutions and facilitating eco-friendly products. Alternatively, cyber-physical systems and intelligent manufacturing execution systems contribute to sustainability via increasing productivity, resource efficiency, and waste reduction across various industrial operations. Therefore, the sustainable manufacturing outcomes of Industry 4.0 depend on how manufacturers perceive this phenomenon and its underlying technologies, design principles, and sustainability functions. The superadditive synergies among Industry 4.0 technologies, design principles, and the underlying sustainability functions determine how digitalization efforts at the corporate and value chain levels would contribute to sustainable development.
- Industry 4.0 is the digital transformation of industrial value creation processes, which involves implementing modern digital technologies and developing complex design principles. Industry 4.0 digital transformation is a gradual process of providing value partners with new value creation and delivery methods concerning the entire product and service life-cycle. It is why Industry 4.0 offers massive opportunities for sustainable manufacturing, given that they both concern the optimization of the entire product life cycle, value creation, and delivery channels.
- Sustainable manufacturing is multidimensional, involving sustainable development for the economy, environment, and society. Sustainable manufacturing requires all stakeholders' involvement in sustainable value co-creation, and the seamless integrative nature of Industry 4.0 enable value chain partners and even customers to converge with sustainability. Findings reveal that supply chain process integration is the stepping stone toward sustainable manufacturing under the Industry 4.0 scenario, emphasizing value chain thinking for sustainable development.
- The socio-environmental implication of Industry 4.0 should be viewed from the lens of manufacturing-economic opportunities that digital transformation offers to the manufacturing industry. Without economic sustainability, manufacturers will not have the liberality to prioritize environmental preservation and social development, as corporate survival becomes the sole strategic priority.
- Not all functions identified within this study are intrinsically sustainable. Each of the 15 functions holds specific potential for enabling or contributing to particular aspects of sustainable manufacturing. For example, business model innovation is not inherently socio-environmentally friendly. Business model innovation can promote environmental sustainability by enabling green product and process innovation or may contribute to social sustainability by enabling product personalization and customer-orientation strategy. A unidimensional business model can overvalue manufacturing-economic productivity and worsen socio-environmental sustainability impacts if designed and managed poorly. Thus, the 15 sustainable manufacturing functions of Industry 4.0 should be effectively managed based on each manufacturer's idiosyncratic business environment, so the resulting manufacturing ecosystem offers a healthy balance between the triple bottom lines.

The contribution of theoretical studies to the Industry 4.0-sustainable manufacturing research discipline has been impressive. Nonetheless, the discipline is in its embryonic stage, calling for future research to empirically address the speculations regarding the effect of Industry 4.0 on sustainable development. Scholars argue that Industry 4.0 falls short in contributing to the socio-environmental aspect of sustainable development at the macro-regional scales, introducing new agendas such as Industry 5.0 to address these concerns. Thus, the impact of Industry 4.0 and automation on job displacement, corporate inequality, income inequality, digital divide, rebound effect, and overconsumption requires further empirical elaboration. Besides, an empirical assessment of policies or economic trends on Industry 4.0-sustainability interaction offers exciting opportunities for future research. More importantly, future studies are invited to study the manufacturing sustainability implications of Industry 4.0 from the perspective of digital technologies enabling manufacturers to deal with unpredictable crises such as COVID-19. In addition, the Industry 4.0 contribution roadmap for sustainable manufacturing developed in the present study might appear hard to interpret, mainly due to the complexity and interconnectivity of Industry 4.0 functionalities for sustainability. Future research can offer more accessible insights to practitioners and policymakers by scrutinizing and empirically exploring each micro-function identified within the Industry 4.0 sustainable manufacturing roadmap in this study. Finally, yet importantly, the present study could not conceivably measure the sustainability impacts of individual Industry 4.0 technologies. Considering the complexity of Industry 4.0, future studies are invited to explore how Industry 4.0 technologies, quality of their integration, and synergies among them may impact the sustainability outputs of manufacturing digitalization under Industry 4.0.

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

Table A1
Hierarchy level for Industry 4.0 sustainable manufacturing functions.

Factors	Reachability set	Antecedent set	Intersection set	level
Iteration I				
BUMI	BUMI, CUOM, HAER, IMPM, MANA, MAPE, NEEP, REEE, REMC, SUPD, SVCN	BUMI, SCPI	BUMI	
CUOM	CUOM, IMPM, NEEP, REEE, SUPD, SVCN	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SCPI	CUOM, IMPM, REEE	
EMPP	CUOM, EMPP, HAER, IMPM, IPPC, MANA, MAPE, NEEP, REEE, REMC, SUPD, SVCN	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
HAER	*HAER*	*BUMI, EMPP, HAER, IMPM, IPPC, MANA, MAPE, REEE, SSWE, SCPI, SUPD, SVCN*	*HAER*	*I*
IMPM	CUOM, HAER, IMPM, NEEP, REEE, SUPD, SVCN	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SSWE, SCPI, SUPD	CUOM, IMPM, REEE, SUPD	
IPPC	CUOM, EMPP, HAER, IMPM, IPPC, MANA, MAPE, REEE, REMC, SUPD	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
MANA	CUOM, HAER, IMPM, MANA, MAPE, NEEP, REEE, REMC, SUPD, SVCN	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
MAPE	CUOM, HAER, IMPM, MANA, MAPE, NEEP, REEE, REMC, SUPD, SVCN	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
NEEP	*NEEP*	*BUMI, CUOM, EMPP, IMPM, MANA, MAPE, NEEP, REEE, REMC, SCPI, SUPD, SVCN*	*NEEP*	*I*
REEE	CUOM, HAER, IMPM, NEEP, REEE, REMC, SUPD, SVCN	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, SSWE, SCPI, SUPD, SVCN	CUOM, IMPM, REEE, SUPD, SVCN	
REMC	CUOM, IMPM, NEEP, REMC, SUPD, SVCN	BUMI, EMPP, IPPC, MANA, MAPE, REEE, REMC, SSWE, SCPI, SUPD	REMC, SUPD	
SSWE	EMPP, HAER, IMPM, IPPC, MANA, MAPE, REEE, REMC, SSWE	SSWE	SSWE	
SCPI	BUMI, CUOM, EMPP, HAER, IMPM, IPPC, MANA, MAPE, NEEP, REEE, REMC, SCPI, SUPD, SVCN	SCPI	SCPI	
SUPD	HAER, IMPM, NEEP, REEE, REMC, SUPD	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SCPI, SUPD, SVCN	IMPM, REEE, REMC, SUPD	
SVCN	HAER, NEEP, REEE, SUPD, SVCN	BUMI, CUOM, EMPP, IMPM, MANA, MAPE, REEE, REMC, SCPI, SVCN	REEE, SVCN	
Iteration II				
BUMI	BUMI, CUOM, IMPM, MANA, MAPE, REEE, REMC, SUPD, SVCN	BUMI, SCPI	BUMI	
CUOM	CUOM, IMPM, REEE, SUPD, SVCN	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SCPI	CUOM, IMPM, REEE	
EMPP	CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SUPD, SVCN	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
IMPM	CUOM, IMPM, REEE, SUPD, SVCN	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SSWE, SCPI, SUPD	CUOM, IMPM, REEE, SUPD	
IPPC	CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SUPD	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
MANA	CUOM, IMPM, MANA, MAPE, REEE, REMC, SUPD, SVCN	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
MAPE	CUOM, IMPM, MANA, MAPE, REEE, REMC, SUPD, SVCN	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
REEE	CUOM, IMPM, REEE, REMC, SUPD, SVCN	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, SSWE, SCPI, SUPD, SVCN	CUOM, IMPM, REEE, SUPD, SVCN	
REMC	CUOM, IMPM, REMC, SUPD, SVCN	BUMI, EMPP, IPPC, MANA, MAPE, REEE, REMC, SSWE, SCPI, SUPD	REMC, SUPD	
SSWE	EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SSWE	SSWE	SSWE	
SCPI	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SCPI, SUPD, SVCN	SCPI	SCPI	
SUPD	*IMPM, REEE, REMC, SUPD*	*BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SCPI, SUPD, SVCN*	*IMPM, REEE, REMC, SUPD*	*II*
SVCN	REEE, SUPD, SVCN	BUMI, CUOM, EMPP, IMPM, MANA, MAPE, REEE, REMC, SCPI, SVCN	REEE, SVCN	
Iteration III				
BUMI	BUMI, CUOM, IMPM, MANA, MAPE, REEE, REMC, SVCN	BUMI, SCPI	BUMI	
CUOM	CUOM, IMPM, REEE, SVCN	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SCPI	CUOM, IMPM, REEE	
EMPP	CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SVCN	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
IMPM	CUOM, IMPM, REEE, SVCN	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SSWE, SCPI,	CUOM, IMPM, REEE	
IPPC	CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
MANA	CUOM, IMPM, MANA, MAPE, REEE, REMC, SVCN	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
MAPE	CUOM, IMPM, MANA, MAPE, REEE, REMC, SVCN	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
REEE	CUOM, IMPM, REEE, REMC, SVCN	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, SSWE, SCPI, SVCN	CUOM, IMPM, REEE, SVCN	
REMC	CUOM, IMPM, REMC, SVCN	BUMI, EMPP, IPPC, MANA, MAPE, REEE, REMC, SSWE, SCPI	REMC	
SSWE	EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SSWE	SSWE	SSWE	
SCPI	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SCPI, SVCN	SCPI	SCPI	
SVCN	*REEE, SVCN*	*BUMI, CUOM, EMPP, IMPM, MANA, MAPE, REEE, REMC, SCPI, SVCN*	*REEE, SVCN*	*III*
Iteration IV				
BUMI	BUMI, CUOM, IMPM, MANA, MAPE, REEE, REMC	BUMI, SCPI	BUMI	

(*continued on next page*)

Table A1 (*continued*)

Factors	Reachability set	Antecedent set	Intersection set	level
CUOM	*CUOM, IMPM, REEE*	*BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SCPI*	*CUOM, IMPM, REEE*	*IV*
EMPP	CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
IMPM	*CUOM, IMPM, REEE*	*BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SSWE, SCPI,*	*CUOM, IMPM, REEE*	*IV*
IPPC	CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
MANA	CUOM, IMPM, MANA, MAPE, REEE, REMC	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
MAPE	CUOM, IMPM, MANA, MAPE, REEE, REMC	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
REEE	CUOM, IMPM, REEE, REMC	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, SSWE, SCPI	CUOM, IMPM, REEE	
REMC	CUOM, IMPM, REMC	BUMI, EMPP, IPPC, MANA, MAPE, REEE, REMC, SSWE, SCPI	REMC	
SSWE	EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SSWE	SSWE	SSWE	
SCPI	BUMI, CUOM, EMPP, IMPM, IPPC, MANA, MAPE, REEE, REMC, SCPI	SCPI	SCPI	
Iteration V				
BUMI	BUMI, MANA, MAPE, REEE, REMC	BUMI, SCPI	BUMI	
EMPP	EMPP, IPPC, MANA, MAPE, REEE, REMC	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
IPPC	EMPP, IPPC, MANA, MAPE, REEE, REMC	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
MANA	MANA, MAPE, REEE, REMC	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
MAPE	MANA, MAPE, REEE, REMC	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
REEE	REEE, REMC	BUMI, EMPP, IPPC, MANA, MAPE, REEE, SSWE, SCPI	REEE	
REMC	*REMC*	*BUMI, EMPP, IPPC, MANA, MAPE, REEE, REMC, SSWE, SCPI*	*REMC*	*V*
SSWE	EMPP, IPPC, MANA, MAPE, REEE, REMC, SSWE	SSWE	SSWE	
SCPI	BUMI, EMPP, IPPC, MANA, MAPE, REEE, REMC, SCPI	SCPI	SCPI	
Iteration VI				
BUMI	BUMI, MANA, MAPE, REEE	BUMI, SCPI	BUMI	
EMPP	EMPP, IPPC, MANA, MAPE, REEE	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
IPPC	EMPP, IPPC, MANA, MAPE, REEE	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
MANA	MANA, MAPE, REEE	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
MAPE	MANA, MAPE, REEE	BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI	MANA, MAPE	
REEE	*REEE*	*BUMI, EMPP, IPPC, MANA, MAPE, REEE, SSWE, SCPI*	*REEE*	*VI*
SSWE	EMPP, IPPC, MANA, MAPE, REEE, SSWE	SSWE	SSWE	
SCPI	BUMI, EMPP, IPPC, MANA, MAPE, REEE, SCPI	SCPI	SCPI	
Iteration VII				
BUMI	BUMI, MANA, MAPE	BUMI, SCPI	BUMI	
EMPP	EMPP, IPPC, MANA, MAPE	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
IPPC	EMPP, IPPC, MANA, MAPE	EMPP, IPPC, SSWE, SCPI	EMPP, IPPC	
MANA	*MANA, MAPE*	*BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI*	*MANA, MAPE*	*VII*
MAPE	*MANA, MAPE*	*BUMI, EMPP, IPPC, MANA, MAPE, SSWE, SCPI*	*MANA, MAPE*	*VII*
SSWE	EMPP, IPPC, MANA, MAPE, SSWE	SSWE	SSWE	
SCPI	BUMI, EMPP, IPPC, MANA, MAPE, SCPI	SCPI	SCPI	
Iteration VIII				
BUMI	*BUMI*	*BUMI, SCPI*	*BUMI*	*VIII*
EMPP	*EMPP, IPPC*	*EMPP, IPPC, SSWE, SCPI*	*EMPP, IPPC*	*VIII*
IPPC	*EMPP, IPPC*	*EMPP, IPPC, SSWE, SCPI*	*EMPP, IPPC*	*VIII*
SSWE	EMPP, IPPC, SSWE	SSWE	SSWE	
SCPI	BUMI, EMPP, IPPC, SCPI	SCPI	SCPI	
Iteration IX				
SSWE	*SSWE*	*SSWE*	*SSWE*	*IX*
SCPI	*SCPI*	*SCPI*	*SCPI*	*IX*

Table A2
The enabling role of individual sustainability functions.

Causal relationship	Enabling role
Supply chain process integration (SCPI)	
SCPI→BUMI	Supplier and customer integration for service orientation; informed innovation strategy development; cross-functional collaboration
SCPI→CUOM	Customer information integration; collaborative new product development
SCPI→IMPM	Optimized supply and payment strategies; flexible reaction to supply situations and turbulent demands; supply chain efficiency
SCPI→IPPC	Supply chain information flow integration; collaborative production scheduling
SCPI→MANA	Customer behavior prediction; supply chain-wide process visibility and control; collaborative manufacturing
SCPI→MAPE	On-time material delivery; removal of information silos; collaborative performance measurement and monitoring
SCPI→SUPD	Sustainable process alignment; collaborative green research and development
SCPI→SVCN	Sustainability co-governance; sustainable procurement and purchasing; sustainable value co-creation
Safe and smart working environment (SSWE)	
SSWE→EMPP	Working comfort; employee empowerment; onsite interactive training; informed decision making
SSWE→MAPE	Reduced human errors; enhanced sense of ownership among employees; reduced equipment failures; reduced workplace accidents
Employee productivity (EMPP)	
EMPP→IMPM	Reduced labor costs; reduced cost of quality; reduced maintenance costs

(*continued on next page*)

Table A2 (*continued*)

Causal relationship	Enabling role
EMPP→IPPC	Production-planning requirements assessment accuracy; stable production capacity; forecast accuracy
EMPP→MANA	Teamwork and collaboration efficiency; agile learning culture; less resistance to change
EMPP→MAPE	Reduced defect rate; reduced rework; improved equipment management; improved equipment life cycle
EMPP→REEE	Improved performance accountability; production reliability; Improved throughput
EMPP→REMC	Reduced waste; reduced resource consumption; reduced cost of breakdowns; lower indirect overhead costs
Business model innovation (BUMI)	
BUMI→CUOM	Customer-oriented business models (e.g., product-as-a-service business model); customer experience-focused strategies
BUMI→IMPM	Manufacturing servitization; product individualization
BUMI→MAPE	Operationalization of novel processes, management practices, and collaboration strategies
BUMI→MANA	Streamlined information sharing; agile operating model; active partnership culture; team-based value delivery channels
BUMI→REEE	Continuous improvement mindset; sustainable thinking; industrial symbioses; sustainable product design approach
BUMI→NEEP	New talent acquisition for skill development, data analytics, problem-solving, and idea generation; employment-friendly service and product innovation; employment-friendly organizational change
Intelligent production planning and control (IPPC)	
IPPC→CUOM	Better services to customers; dynamic order fulfillment; improved customer delivery performance
IPPC→EMPP	Communication efficiency; reduced employee idle time; optimized employee shift scheduling
IPPC→MANA	Dynamic raw material procurement; flexible work schedules; better decision making
IPPC→MAPE	Optimized inventory; higher equipment availability; reduced idle time; reliable input availability
Manufacturing agility (MANA)	
MANA→CUOM	Rapid response to the customer demand fluctuation; rapid prototyping; dynamic product and service development
MANA→IMPM	Increased value of personalized products; streamlined operations, and reduced operating expenses
MANA→MAPE	Strong supply base; modular production design; decentralized decision-making
MANA→REMC	Reduced product time to market; reduced production reconfiguration cost, reduced inventory cost
Manufacturing productivity and efficiency (MAPE)	
MAPE→HAER	Electricity, water, fuel, and raw material consumption optimization across the supply chain
MAPE→IMPM	Improved product quality; reduced unit cost of products; reduced warranty costs
MAPE→MANA	Higher workforce flexibility; higher responsiveness to business, market, and environmental changes
MAPE→REEE	Waste tracking and minimization, machine breakdown prevention; optimized defect management strategies
MAPE→REMC	Increased production rate; reduced production disruption; less work-in-process, reduced storage and waiting time
Resource and energy efficiency (REEE)	
REEE→HAER	Reduced material handling and transportation; resource recycling; opportunities for integrating renewable energy resources
REEE→IMPM	Reduced compliance cost; cost leadership-based market growth
REEE→REMC	Reduced raw material costs; reduced energy cost; minimized maintenance cost for resource/energy distribution system
Reduced manufacturing costs (REMC)	
REMC→CUOM	Cost-competitive individualized products; financing reconfigurable and flexible manufacturing system
REMC→IMPM	Higher product profit margin; higher vendor profit share, and increased market penetration of products
Customer-oriented manufacturing (CUOM)	
CUOM→IMPM	Customer satisfaction; improved brand image; customer loyalty; premium product and service monetization plans
CUOM→SUPD	Customer-integrated eco-design of products; customer-driven life-cycle thinking-based new products
Improved manufacturing profit margin (IMPM)	
IMPM→CUOM	Investment in developing flexible and decentralized manufacturing systems for adopting the market-push approach
IMPM→NEEP	Launching new product lines, implementing skill-intensive new technologies; increasing production capacity
IMPM→SUPD	Increased green research and development budget for eco-innovation and digital twin-based product life cycle analysis (e.g., virtual prototyping)
IMPM→SVCN	More capital available for sustainable value co-creation initiatives across supply networks
Sustainable value-creation networking (SVCN)	
SVCN→HAER	Supply chain-wide emission audits; collaborative optimization of resource consumption, space utilization, and transportation
SVCN→NEEP	New jobs in the areas of collaborative product and service life-cycle assessment, sustainable service development, and sustainable transportation management
SVCN→SUPD	Collaborative product environmental assessment, green product ideation; eco-friendly stipulations on new product launches across the value chain
Sustainable product development (SUPD)	
SUPD→NEEP	New jobs in the area of additive manufacturing, rapid prototyping, digital twins, and high-performance computing computer-aided design
SUPD→REEE	Recyclable waste; product modularity; reduced material intensity; proactive product function improvement; integration of renewable resources; design for remanufacturing

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Glossary

BUMI: Business model innovation
CUOM: Customer-oriented manufacturing
EMPP: Employee productivity
EXC: Exclusion criterion
FRM: Final Reachability Matrix
HAER: Harmful emission reduction
IMPM: Improved manufacturing profit margin
INC: Inclusion criterion
IPPC: Intelligent production planning and control
IRM: Initial Reachability Matrix
ISM: Interpretive Structural Modeling
MANA: Manufacturing agility
MAPE: Manufacturing productivity and efficiency
MICMAC: Matrices d'Impacts Croises Multiplication Appliqué an un Classement
NEEP: New employment opportunities
NGT: Nominal Group Technique
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
REEE: Resource and energy efficiency
REMC: Reduced manufacturing costs
SCPI: Supply chain process integration
S-LCA: The Social and socio-economic Life Cycle Assessment
SLR: Systematic Literature Review
SSIM: Structural Self-Interaction Matrix
SSWE: Safe and smart working environment
SUPD: Sustainable product development
SVCN: Sustainable value-creation networking
TBL: Triple Bottom Line