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Review

Industry 4.0, digitization, and opportunities for sustainability

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ABSTRACT

The fourth industrial revolution and the underlying digital transformation, known as Industry 4.0, is progressing exponentially. The digital revolution is reshaping the way individuals live and work fundamentally, and the public remains optimistic regarding the opportunities Industry 4.0 may offer for sustainability. The present study contributes to the sustainability literature by systematically identifying the sustainability functions of Industry 4.0. In doing so, the study first reviews the fundamental design principles and technology trends of Industry 4.0 and introduces the architectural design of Industry 4.0. The study further draws on the interpretive structural modelling technique to model the contextual relationships among the Industry 4.0 sustainability functions. Results indicate that sophisticated precedence relationships exist among various sustainability functions of Industry 4.0. 'Matrice d'Impacts Croisés Multiplication Appliquée àun Classement' (MICMAC) analysis reveals that economic sustainability functions such as production efficiency and business model innovation tend to be the more immediate outcome of Industry 4.0, which pays the way for development of more remote socioenvironmental sustainability functions of Industry 4.0 such as energy sustainability, harmful emission reduction, and social welfare improvement. This study can serve Industry 4.0 stakeholders — leaders in the public and private sectors, industrialists, and academicians — to better understand the opportunities that the digital revolution may offer for sustainability, and work together more closely to ensure that Industry 4.0 delivers the intended sustainability functions around the world as effectively, equally, and fairly as possible.

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1. Introduction

At the dawn of the 21st century, the world is witnessing the fourth industrial revolution and the digital transformation of the business world, which is commonly referred to as Industry 4.0. The fourth industrial revolution is a hit rather than hype (Ardito et al., 2019; Buer et al., 2018; Schroeder et al., 2019). Since the publicisation of the term "Industrie 4.0" in 2011, the digital transformation necessitated by Industry 4.0 immediately captured the attention of industrialists and governments worldwide (Ghobakhloo, 2018; Nascimento et al., 2019). Since the first industrial revolution in 18th century, the world has been dealing with the challenge of producing more goods from limited and depleting natural resources to meet the ever-growing consumption demand while limiting negative environmental and social impacts (Beier et al., 2018; Müller et al., 2018a). Consistently, the sustainability impacts of Industry 4.0 and the way it can contribute to the sustainable economic, environmental, and social development is increasingly gaining attention.

Sustainability is a broad concept addressing most aspects of the human world (Beier et al., 2017). Sustainability is not limited to the environmentalism, as it also involves preserving economic and social resources (Choi and Ng, 2011; Ford and Despeisse, 2016). United Nations defines sustainability as a movement for ensuring a better and more sustainable wellbeing for all, including the future generations, which aims to address the everlasting global issues of injustice, inequality, peace, climate change, pollution, and environmental degradation. Although sustainability is a relatively new concept, however, its roots are in the enduring movements such as conservationism or socio-economic justice (Caradonna, 2014). Sustainability has a rich literature, and academia has made a significant contribution to the conceptualization and materialization of its three underlying pillars of environmental, economic, and social sustainability (Ford and Despeisse, 2016; Kamble et al., 2018; Khuntia et al., 2018). *Environmental sustainability* is mainly concerned with maintaining the earth's environmental systems equilibrium, the balance of natural resources consumption and replenishment, and ecological integrity (Glavič and Lukman, 2007). *Economic sustainability* concerns long-term economic growth while preserving environmental and social resources. Viewed from this perspective, the growth of economic capital should not be at the expense of the decrease in natural or social capital. Thus, economic growth should not ignore the balance in natural resources, ecosystems, social welfare, and distribution of wealth (Choi and Ng, 2011). *Social sustainability* is the process of recognizing and managing the positive and negative business, environmental, economic, and technological impacts on people. Social sustainability ultimate goal is the creation of healthy and liveable communities where everyone is protected from discrimination and has access to universal human rights and basic amenities such as security or healthcare (Dempsey et al., 2011). Sustainability is indispensable because of a simple reason; Earth's ecosystems and the desired quality of humankind's life cannot be maintained without human beings embracing sustainability (Caradonna, 2014; Glavič and Lukman, 2007). Consistently, the sustainability impacts of Industry 4.0 merit the full attention of academia given preceding industrial revolutions resulted in dramatic and somewhat unexpected economic, environmental, and social changes. Despite being in its infancy, the unforeseen or unintended consequences of Industry 4.0 and digital transformation on triple bottom line sustainability are expected to be consequential (Jabbour et al., 2018a; Kamble et al., 2018).

In the Industry 4.0 environment, the interconnected computers, smart materials, and intelligent machines communicate with one another, interact with the environment, and eventually make decisions with minimal human involvement (Gilchrist, 2016). The digital connectedness and information development and sharing, as the true power of Industry 4.0, may have contradictory impacts on triple bottom line (economic, environmental, and social) sustainability (Jabbour et al., 2018 a; b; Kamble et al., 2019; Müller et al., 2018b). Digitizing manufacturing and business processes and deploying smarter machines and devices may offer numerous advantages such as manufacturing productivity, resource efficiency, and waste reduction (Tortorella and Fettermann, 2018). In contrast, an increased rate of production thanks to industrial automation would be associated with higher resource and energy consumption as well as elevated pollution concerns (Beier et al., 2017; Liu and Bae, 2018). Viewed from the social development perspective, digital transformation and the restructuring of the industry are expected to disrupt the labour market severely. Experts believe digitization and the emergence of labour-saving technologies (e.g., intelligent robots, autonomous vehicles, and cloud solutions) will eliminate the majority of lower-skilled jobs while creating countless job opportunities in various areas such as automation engineering, control system design, machine learning, and software engineering (Brougham and Haar, 2018; Frey and Osborne, 2017).

The research on the sustainability impact of the fourth industrial revolution is in its nascence, and the sustainability implications of Industry 4.0 in terms of economic, environmental, and social impacts of manufacturing digitization requires further exploration. The present study addresses this issue by modelling the process through which Industry 4.0 - characterized by its underlying digital technologies and design principles – can positively contribute to sustainable economic, environmental, and social development. Therefore, the study first offers a concise discussion on the concept of Industry 4.0 phenomenon and its functionalities. The study further employs Interpretive Structural Modelling (ISM) to identify Industry 4.0 functions for sustainability. In doing so, the study first performs a state-of-the-art content-driven review and analysis of the literature to identify the critical sustainability functions of Industry 4.0. After capturing the opinions of smart manufacturing, digitization, and sustainability experts, and further mapping the interrelationships among sustainability functions identified, the study performs 'Matrice d'Impacts Croisés Multiplication Appliquée àun Classement' (MICMAC) analysis and obtains the driving and dependence power of the sustainability functions. Finally, the study discusses the findings and explains how the underlying design principles and technology trends of Industry 4.0 can function favourably in support of sustainability.

2. Industry 4.0 modality

Originally, Industry 4.0 was conceptualized as the fourth revolution that has arisen in the manufacturing industry, yet this conceptualization has evolved during the past few years (Xu et al., 2018). Industry 4.0 nowadays involves the digital transformation of the entirety of industrial and consumer markets, from the advent of smart manufacturing to digitization of entire value delivery channels (Schroeder et al., 2019). Consistently, academia and governmental and industrial collaborators narrate Industry 4.0 to the digitization and smartization of factories, distribution channels, and value chain members (Kang et al., 2016; Liao et al., 2017; Qu et al., 2019).

To facilitate the understandability of Industry 4.0 concept, prior scholars tend to describe this phenomenon based on its underlying design principles and technology trends (Gilchrist, 2016; Zheng et al., 2018). Ghobakhloo (2018, pp. 911–912) explains that the design principles of Industry 4.0 "are what that explicitly address the issue of Industry 4.0 vagueness by providing a systemization of knowledge and describing the constituents of this phenomenon …. These design principles enable manufacturers to foresee the adaptation progress of Industry 4.0 and grant them the "how to do" knowledge in developing appropriate procedure and solutions required for Industry 4.0 transition … technology trends simply refer to the advanced digital technological innovations that, collectively, enable the rise of the new digital industrial technology, known as Industry 4.0." Table 1 reviews the previous studies contributing to the conceptualization of Industry 4.0 and lists the fundamental design principles and technology trends of Industry 4.0 available within the literature. Fig. 1 describes the scope of Industry 4.0 and the functionality of its components. To achieve its underlying design principles, the digital transformation under Industry 4.0 relies on the implementation and integration of a variety of simple to advanced Information, Digital, and Operation Technologies (IDOT) such as industrial sensors, industrial controllers, Automated Guided Vehicles (AGV), robots, Augmented and Virtual Reality (AVR), data analytics, cloud computing, Internet of Services (IoS), High-Performance Computing-powered Computer-Aided Design and Manufacturing (HPC-CADM), and Artificial Intelligence (AI) (Chen et al., 2017; Hofmann and Rüsch, 2017; Lasi et al., 2014; Lu, 2017). Many of the enabling IDOT of Industry 4.0 has been available to Industrialists during the past four decades (Chen et al., 2017; Gilchrist, 2016). However, they are very recently coming to maturity in terms of integrability and interoperability necessary for digitization (Nascimento et al., 2019; Yin et al., 2018).

Nonetheless, advanced technology trends of Industry 4.0, such as the Industrial Internet of Things (IIoT) or Cyber-Physical Production Systems (CPPS) are not off-the-shelf technological products (Ghobakhloo and Ng, 2019). These sophisticated technologies rely on the implementation and integration of various combinations of IDOT across value networks. IIoT and CPPS for example, as overlapping and interconnected concepts, rely on the integration of AI, machine-to-machine communication, industrial controllers, smart sensors, cloud data, big data analytics, and semantic technologies to create a dynamic cyber-physical control system ensuring efficiency and reliability of industrial operations (Sisinni et al., 2018; Wan et al., 2016). Overall, none of the technology trends of Industry 4.0 operates independently (Gilchrist, 2016). The dependence and integratedness of Industry 4.0 do not function as a limitation given these conditions contribute to the *interoperability* feature of Industry 4.0 (Li, 2018). Interoperability ensures that various components of a value network such as control systems, intelligent equipment and machinery, smart materials and products, connected customers, decision systems, and human resources to connect, communicate, and share data in a coordinated way (Tortorella and Fettermann, 2018; Vogel-Heuser and Hess, 2016; Zheng et al., 2018).

As clearly explained in Fig. 1, Industry 4.0 digital transformation involves the digitization and integration of the entire value chain of the lifecycle of products. The Digital Supply Network (DSN) offers a *vertically* and *horizontally* integrated supply network within which all the value functions such as smart suppliers, connected customers, smart factories, production machinery, smart products, and intelligent materials interact and communicate with each other in real-time and at the global scale (Ardito et al., 2019; Bechtsis et al., 2018; Kache and Seuring, 2017). This level of integration is enabled by IoS and Internet of People (IoP) integrating customers and products into the DSN and facilitating the development of the Product-as-a-Service (PaaS) business model (Ghobakhloo, 2018). At the smart factory level, the application of CPPS, IIoT, big data analytics, and cloud data leads to the production *decentralization* that enables machines, human resources, materials, and process controllers intercommunicate in real-time as naturally as in a social network (Chen et al., 2017; Longo et al., 2017; Wang et al., 2016). The sheer amount of communication efficiency, transparency, surveillance, and control in the smart factory minimizes downtime, waste, defect, and risk across production processes (Buer et al., 2018; Ghobakhloo and Ng, 2019; Schroeder et al., 2019).

The *virtualization* principle of Industry 4.0 and the conversion of sensor data acquired from the physical world into digital twin (simulation-based) models of smart components (e.g., new products, production machinery, or even the entire smart factory) across the value network offers invaluable opportunities for prediction and optimization of manufacturing operations (Leng et al., 2019; Qi and Tao, 2018). For example, the product development team can use the digital twin of new products to simulate the real future use of the physical products and assess the digital footprint of products throughout their lifecycle (Tao et al., 2018a). Alternatively, the use of AVR, industrial robotics, automation, and additive manufacturing for the development of the modularity principle of Industry 4.0 facilitates an agile, flexible, and decentralized production environment that effectively adapts to the ever-changing customer requirements (Kumar, 2018; Niaki et al., 2019; Posada et al., 2015). Besides meeting customers' current demands and preferences, the use of IoP, big data analytics, and simulation for customer behaviour modelling and market sensing gravely supports the modular

Table 1
Fundamental design principles and technology trends of Industry 4.0.

Research	Design principles											
	Decentralization		Horizontal Integration	Interoperability	Modularity	Product and service individualization	Real-Time Capability	Service Orientation	Smart Factory	Smart Product	Vertical Integration	Virtualization
Ardito et al. (2019)		x								x		x
Braccini and Margherita (2019)												x
Fatorachian and Kazemi (2018)					x							
Ghobakhloo (2018)	x	x	x	x	x	x	x	x	x	x	x	x
Ghobakhloo (2019)	x	x	x	x		x		x	x	x	x	x
Gilchrist (2016)	x	x	x	x		x	x	x	x	x	x	x
Hofmann and Rüsch (2017)		x				x	x	x				x
Jabbour et al. (2018a, b)												x
Junior et al. (2018)		x	x	x					x	x		
Kamble et al. (2019)		x				x				x		x
Kang et al. (2016)		x	x			x				x		x
Lasi et al. (2014)	x	x						x	x	x		
Lee et al. (2015)												
Li (2018)	x		x					x			x	
Liao et al. (2017)	x	x							x	x	x	x
Lu (2017)	x	x	x	x		x	x	x	x	x	x	
Moeuf et al. (2018)												
Mohamed et al. (2019)		x								x	x	x
Mosterman and Zander (2016)												
Posada et al. (2015)		x			x		x			x	x	
Qi and Tao (2018)											x	
Roblek et al. (2016)		x			x			x	x			
Sikorski et al. (2017)												
Strandhagen et al. (2017)		x				x		x		x		x
Strange and Zucchella (2017)		x				x						x
Sung (2018)	x		x			x					x	
Theorin et al. (2017)							x			x		
Tortorella and Fettermann (2018)	x		x	x		x	x				x	x
Vogel-Heuser and Hess (2016)			x	x		x	x				x	
Wan et al. (2016)												
Wang et al. (2016)				x	x							
Wang et al. (2017)					x							
Wollschlaeger et al. (2017)								x	x			
Zhang et al. (2019)	x		x			x		x	x			
Zhang et al. (2019)	x								x			

production system of the smart factory in achieving the ultimate goal of *product individualization* (Torn and Vaneker, 2019; Wang et al., 2017; Yang et al., 2017).[1]

3. The ISM model of industry 4.0 sustainability functions

To identify the sustainability functions of Industry 4.0 and the interrelationships among them, the study applies the ISM technique. ISM (Warfield, 1982), as an adaptation of Paired Comparison, is a reliable and widely-applied decision-making approach that facilitates the explanation of complex relationships among variables of a real system and transforms them into a meaningful visual model (Fathi et al., 2019; Kaswan and Rathi, 2019). Therefore, ISM is regarded as a causal mapping technique for dealing with complex and subjective problems given it enables a graph-theoretic analysis of intricate socioeconomic systems (Raut and Gardas, 2018; Wu et al., 2018). The review of operations management and research literature shows that ISM methodology has been vastly used for examining the causal relationships among components of a particular phenomenon (Thirupathi and Vinodh, 2016; Wu et al., 2018). For example, ISM has been used for modelling of lean manufacturing success (Ghobakhloo et al., 2018a), responsible consumption and production (Wang et al., 2018), logistics sustainability (Govindan et al., 2015; Lim et al., 2017; Raut and Gardas, 2018), tourism sustainability (Tseng et al., 2018a,b), smart manufacturing technology implementation (Ghobakhloo, 2019), green lean Six Sigma (Kaswan and Rathi, 2019), environmental sustainability boundary enablers (Dev and Shankar, 2016), sustainable manufacturing, (Thirupathi and Vinodh, 2016), and the triple bottom line benefits (Wu et al., 2018). The decision for using ISM to identify the sustainability functions of Industry 4.0 is supported by following advantages of this technique (Dev and Shankar, 2016; Raut and Gardas, 2018):

- ISM draws on theoretical, conceptual, and computational resources to extract the intricate pattern of conceptual relations between variables of interest;
- ISM offers a more logical analysis of the interrelationships within variables of a system via a graphical model;
- ISM systematically captures the opinions, judgments, and knowledge base of experts while allowing them the opportunity for revising their judgments;
- The resulting structural model can contribute to the theory building by serving as the input model for causal modelling-based confirmatory research.

To identify and establish the direction of the relationships within variables of a system, the ISM draws on the opinion of experts (Tseng et al., 2018a,b). Expert group selection is an essential step for providing sufficient access to expertise. Following the

[1] Gilchrist (2016) and Ghobakhloo (2018) offer a detailed discussion regarding the design principles and technology trends of Indystry 4.0. A comprehensive list of enabling IDOT of Industry 4.0 and their functionalities has been provided within the recent study by Ghobakhloo (2019).

Technology trends												
Additive/Advanced manufacturing	Augmented and virtual reality	Automation and industrial robotics	Big data analytics	Blockchain	Cloud data and computing	Cybersecurity	Cyber-physical production systems	Internet of people	Internet of services	Industrial internet of things	Semantic technologies	Simulation and modelling
x		x		x	x				x		x	
	x	x		x					x			
		x		x		x			x			
x	x	x	x	x	x	x	x	x	x	x	x	
x		x	x	x		x	x	x	x		x	
x	x	x		x	x		x	x	x		x	
			x	x		x		x	x		x	
				x		x			x			
		x		x		x			x			
x	x	x		x	x	x			x		x	
x		x		x	x	x		x	x			
						x					x	
		x				x						
	x	x		x		x	x	x	x			
x	x	x		x	x				x	x	x	
x	x	x		x	x	x		x	x			
x	x	x		x	x	x			x		x	
x	x	x		x	x				x		x	
		x				x			x			
	x	x		x	x				x	x		
x	x	x		x		x			x		x	
	x					x		x	x			
			x		x	x			x	x		
x	x	x		x		x			x			
	x	x				x			x			
	x	x		x				x	x		x	
		x		x	x	x			x			
		x		x	x	x			x			
		x				x			x			
		x		x		x		x	x			
						x			x			
		x		x		x		x	x			
		x		x		x			x			

expert selection background in ISM context (Shen et al., 2016; Yadav and Barve, 2015) as well as the expert seeking literature (Hertzum, 2014; Hofmann et al., 2010), the present study developed and manually executed an Industry 4.0-sustainability expert selection model. The model first identified the initial pool of 27 experts with a history of significant contributions to the digitization, industrial transformation, and sustainability as well as experience in various areas of industrial application of Industry 4.0 technology trends across various world-class manufacturing firms. The retrieval model first applied the accessibility-related factors based on the following terms:

(i) The expert's willingness and availability to participate in the initial interview as well as the main group sessions;
(ii) The cognitive effort involved in communicating with the expert, comprehending the expert's response, and processing the information obtained.

The application of accessibility-related factors reduced the number of potential experts to 19. As the second step of the selection model, a series of semi-structured interviews was conducted with each of the 19 potential experts, within which the following quality-related selection factors were assessed:

(i) The match between the knowledge of an expert and the scope of present research;
(ii) The credibility of the expert's knowledge based on the expert's academic background;
(iii) The recentness of the expert's knowledge and experience.

The application of the quality-related selection factors resulted in the selection model reducing the number of qualified experts to 10. Consistently, the present study followed the ISM methodology and captured the opinions of the group of 10 experts. After recontacting the shortlisted expert group, introducing the objectives and the scope of the study, and receiving their consent form for participation, Nominal Group Technique (NGT) was used for organizing the group sessions and capturing the opinions of the ten experts. NGT is a learning and development instrument for executing reliable group decision-making (Bartunek and Murninghan, 1984), which encourages contributions from participating members (Harvey and Holmes, 2012). Following the standard procedure (Harris and Sherblom, 2018), the use of NGT technique in this research included seven steps of (1) sequential preparatory tasks execution, (2) participant silent idea generation, (3) round-robin recording of opinions, (4) serial discussion of opinions, (5) preliminary voting on interrelationships, (6) discussion on the preliminary voting, and (7) final voting on interrelationships. The research team, as the meeting facilitator and group leader, ensuring that the threat of bias (e.g., discussion imbalance or opinion invisibility) was minimized during the NGT sessions.

Consistent with the standard procedure in the execution of the ISM technique (e.g., Govindan et al., 2015; Warfield, 1982), the ISM execution in the present study involves steps depicted in Fig. 2.

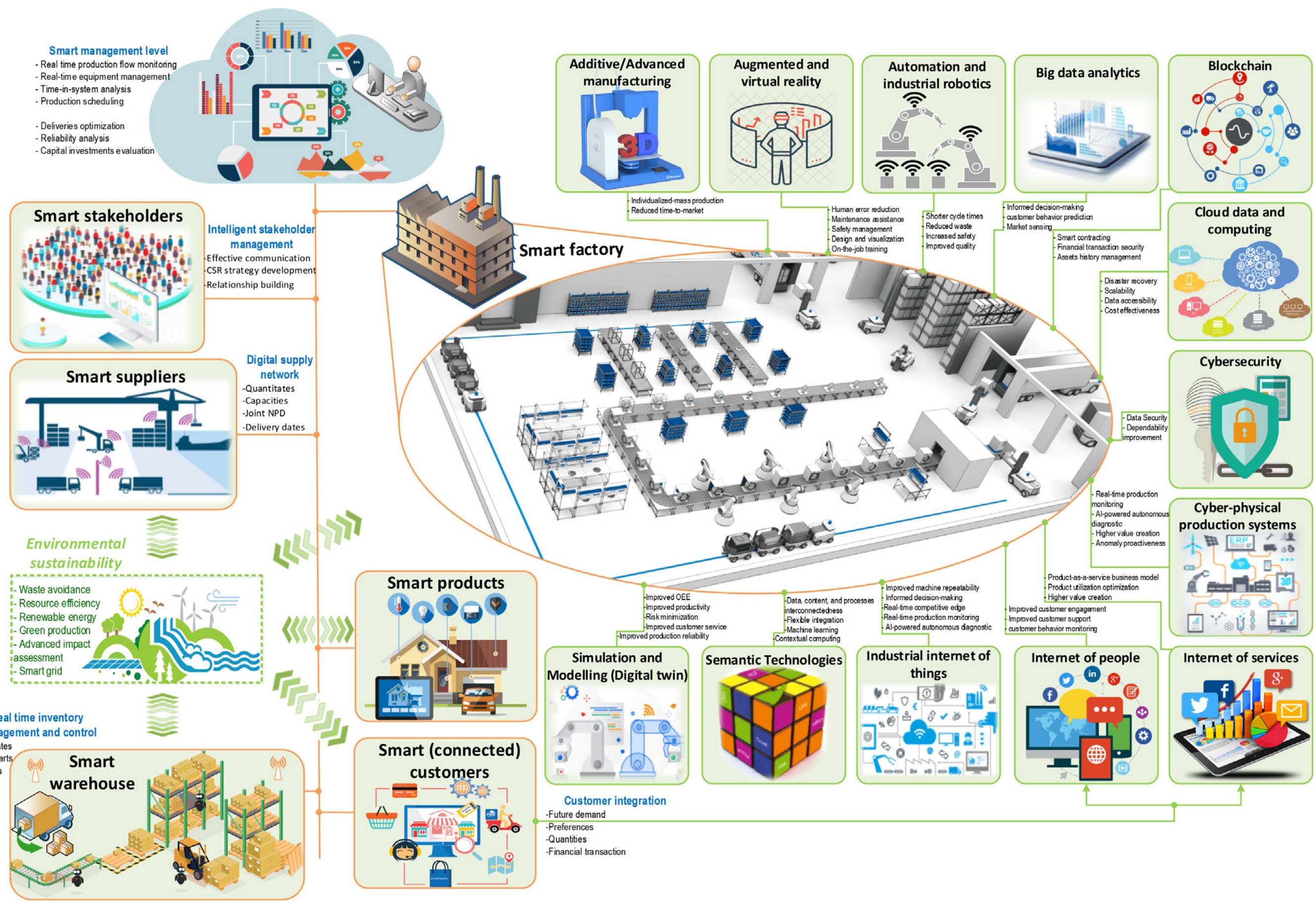

Fig. 1. The architectural design of Industry 4.0.

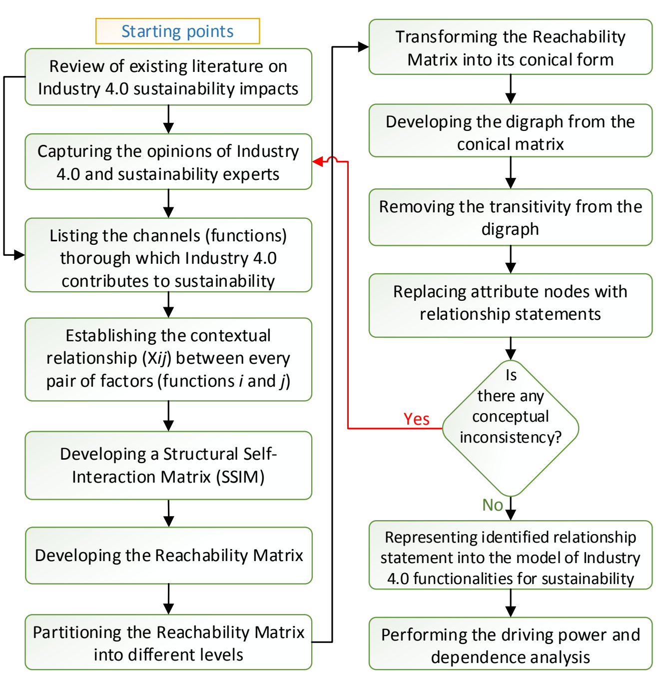

Fig. 2. Steps for obtaining the ISM decision model.

3.1. Identifying industry 4.0 sustainability functions

As the first step of ISM, and to identify Industry 4.0 functions for sustainability, the study followed Webster and Watson (2002) and performed a state-of-the-art content-driven review and analysis of the literature. Fig. 3 offers a schematic presentation of steps undertaken for this purpose. A content-centric review of literature begins with the identification of keywords and search strings. In stage A1 of the review process and to obtain a comprehensive set of suitable journal articles, an advanced search was designed and executed based on the various combinations of keywords related to Industry 4.0 and the concept of sustainability. Following the procedure introduced by Tranfield et al. (2003), the research team collaboratively developed the keywords and search strings from the scoping study and the literature. In the present research, each search string is composed of the 'Industry 4.0-related keywords' AND 'sustainability-related keywords.' *Industry 4.0-related keywords* included the term "Industry 4.0" itself and its synonyms "Industrie 4.0," "fourth industrial revolution," "Industrial internet," and "smart manufacturing." Also, the majority of previous scientific works consider the terms "industrial internet of things" and "cyber-physical systems" as the critical building blocks of the fourth industrial revolution (e.g., Ghobakhloo, 2018; Liao et al., 2017). Therefore, these two terms also were considered as the *Industry 4.0-related keywords*. Alternatively, the present content-centric review consulted the sustainability literature (e.g., Gast et al., 2017;

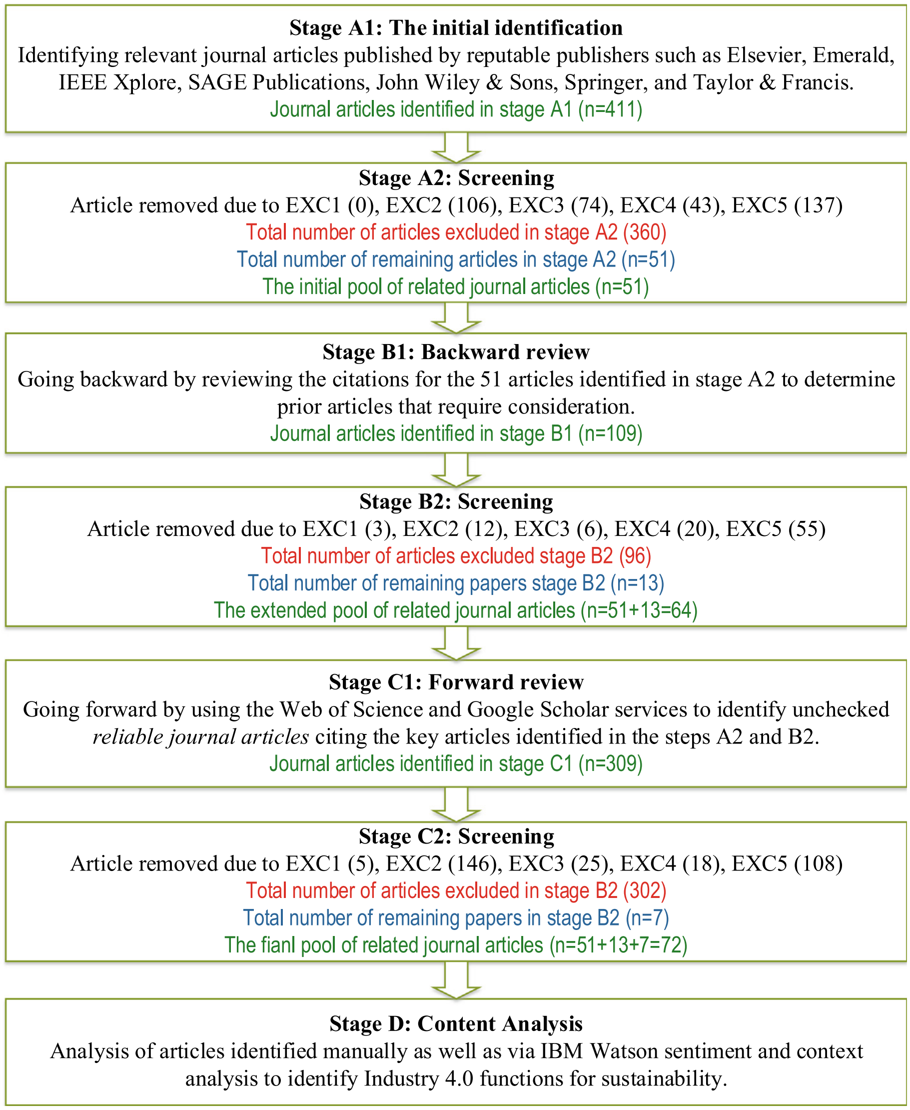

Fig. 3. Steps for the content-driven review and analysis of the literature.

Morioka and De Carvalho, 2016) and selected the eight *sustainability-related keywords* of "sustainability," "economic sustainability," "environmental sustainability," "social sustainability," "value," "benefit," "advantage," and "performance." The initial search attempts via the search string mentioned earlier were executed within reputable online databases such as Elsevier, Emerald, IEEE Xplore, Inderscience, John Wiley & Sons, JStor, MDPI, SAGE, Springer, and Taylor & Francis. The initial search attempts, collectively, identified 411 potentially related journal articles.

At stage A2 of review, each of the 411 initially identified journal articles went through manual content analysis, and the following exclusion criteria were utilized for further screening the articles identified:

EXC1) An article does not have its full text in English;
EXC2) An article uses Industry 4.0, smart manufacturing, or other alternate terms only in title, keywords and/or references;
EXC3) An article uses Industry 4.0 (or the alternate terms) only as a part of the future research direction or future perspective;
EXC4) An article uses Industry 4.0 (or the alternate terms) only as a cited expression;
EXC5) An article does not discuss the benefits, advantages, or sustainability impacts of Industry 4.0, smart manufacturing, or other alternate terms.

As explained in Fig. 3, the application of exclusion criteria to articles identified in stage 1 resulted in the removal of 360 unrelated articles, and the establishment of an initial pool of 51 related journal articles. At stage B1, a backward review of citations for articles shortlisted in stage A2 was conducted in which the reference section of the 51 related articles was analysed. This process led to the identification of 109 new journal articles. In stage B2, the content of the 109 newly identified articles was analysed manually. After subjecting these articles to the exclusion criteria and removal of 96 unrelated articles, the 13 new journal articles were added to the pool of related documents. In stage C1, Google Scholar and Web of Science were used for identifying journal articles that cited the 64 related articles shortlisted through stages A2 and B2. Stage C1 led to identifying 309 new journal articles not recognized during previous steps of the review process. In stage C2, the content of the 309 newly identified articles was manually analysed, and the exclusion criteria were applied to them. Stage C2 resulted in the removal of 302 unrelated articles, and the addition of 7 new journal articles to the pool of related documents increased the total number of related journal articles to 72. At stage D of the review process, and following the procedure introduced by Tranfield et al. (2003), two independent assessors performed the quantitative and thematic analysis of the articles shortlisted, aiming to answer the question of "How can Industry 4.0 and related techno-industrial revolution contribute to various dimensions of sustainability?" In doing so, each of the assessors documented the main ideas, objectives, and contributions of each of the articles shortlisted. Besides extracting research scope, lines, sublines, and objectives, as well as other descriptive information such as methodology, research design, and analytical techniques, each of the assessors, scrutinized the full-text of each of the articles shortlisted and tabulated the contributions identified within the MS Excel database. In a series of meetings, and after sharing individual findings, assessors collectively provided a detailed audit trail back to the core contributions identified, linked themes across the various core contributions wherever possible, and finally reached to a shared consensus. During this process and in order for reducing potential assessor bias, the research team also benefited from the IBM Sentiment and Context Analysis, which enabled the research team to perform the text analysis of selected articles through natural language processing. Via this service, the research team created a custom model for specific *application programming interfaces* to extract necessary results that are tailored to the Industry 4.0-sustainability context. IBM Sentiment and Context Analysis allowed the research team to readily and reliably review the overall sentiment of selected articles and understand their overall negativity and positivity as well as the types of emotion associated. This service also determined essential keywords (e.g., digital technologies or sustainability functions) ranked by relevance and identified essential concepts that were not referenced directly within the text. By parsing selected sentences into their fundamental parts and describing their syntactic roles, IBM Sentiment and Context Analysis enabled the research team to better observe the additional semantic information such as keywords, entities, functions, and hierarchical categories. Table 2 lists the sustainability functions of Industry 4.0 identified. Each of these functions is discussed briefly in the following sections.

3.1.1. *Business model novelty and innovation*

The design principles of Industry 4.0, such as interoperability, decentralization, and real-time capability have drastically changed the way businesses design and deliver their new products and services (Cusumano et al., 2015; Jiang et al., 2016). The emergence of Industry 4.0 has been associated with the introduction and the widespread application of new business model innovations such as Crowd-Sourced Innovation (CSI), Manufacturing as a Service (MaaS), and PaaS (Åkerman et al., 2018; Müller et al., 2018a), which may offer significant economic and social sustainability opportunities (Evans et al., 2017).

3.1.2. *Carbon/harmful gas emission reduction*

Reports indicate that industrial emission is the reason for more than 40 percent of greenhouse gas emissions worldwide (EPA, 2019). Experts believe manufacturing digitization and the emergence of the fourth industrial revolution offers numerous opportunities for the reduction of carbon emission (Ford and Despeisse, 2016; Kamble et al., 2018). IIoT and AI-based production, for example, increase the efficiency and flexibility of production, reduce waste, and minimize carbon emission index per each product (Jin et al., 2017). The opportunities offered by Industry 4.0 for the development of new business models, such as the shift from mass production to the mass customization and even product individualization, can optimize the consumer market and contribute to the materialization of low-carbon future (Müller et al., 2018b, c), further contributing to the environmental and social sustainability (Cai et al., 2019).

3.1.3. *Corporate profitability improvement*

The corporate profitability implications of Industry 4.0 have been widely acknowledged (Hofmann and Rüsch, 2017; Kiel et al., 2017; Müller et al., 2018a). Industrial reports show that the application of Industry 4.0 technology trends such as IIoT, additive manufacturing, cloud service, and data analytics, and the development of design principles of Industry 4.0 such as smart manufacturing and product personalization has been associated with numerous economic sustainability opportunities such as (Dalenogare et al., 2018; Kamble et al., 2019; Wang et al., 2016); (i) material flow optimization, (ii) better time to market of products, (iii) manufacturing space and facility optimization, (iv) resources efficiency, (v) reduction of waste, (vi) superior product innovation and quality, (vii) improved production capacity and reliability, (viii), strategic adaptability, and (ix) lower inventory costs.

3.1.4. *Economic development*

Experts believe when technology trends and design principles of Industry 4.0 are adopted throughout the business ecosystem, digitization can contribute profoundly to the sustainable economic development of countries (Jabbour et al., 2018a; Tseng et al., 2018a,b). Industry 4.0 is expected to act as a job creator instead of a job killer (Frey and Osborne, 2017). Although Industry 4.0 wipes out many low-skilled jobs, however, it creates countless digitization-related job opportunities (Brougham and Haar, 2018). Industry 4.0 would enable countries, less developed ones, in particular, to leapfrog their underachieved industrial development and accelerate the process of economic modernization (Ghobakhloo and Fathi, 2019). Alternatively, operations management sustainability resulted from the adoption of Industry 4.0 digital technologies contributes positively to the development of the circular economy (Stahel, 2016; Tseng et al., 2018a,b). Since Industry 4.0 implications exceed supply chain or production boundaries and involve distribution channels and consumer markets, the spread of Industry 4.0 technologies will have valuable opportunities for various dimensions of sustainable economic development (Cezarino et al., 2019; Lin et al., 2018).

3.1.5. *Energy and resource sustainability*

Digital transformation initiated by Industry 4.0 supports environmental sustainability via sustainable energy and resource transformation (Beier et al., 2017). Industry 4.0 is historically altering the way societies produce, trade, consume, and live. The digitization of energy systems and the widespread application of IDOT, such as wireless networks or blockchain technologies, have offered valuable opportunities for advancing the energy sector (Huang et al., 2017). Smart grids facilitating the integration of power grids and renewable energy sources is an example of digitization implications widely acknowledged within the literature (Batista et al., 2017; Faheem et al., 2018). The sustainability implications of Industry 4.0 are not limited to energy sustainability. More efficient production systems, and the emergence of advanced digital manufacturing technologies (such as CPPS, additive manufacturing, and intelligent robotics), smart material planning and allocation systems, or intelligent materials have contributed to material efficiency and saving significantly (Jose and Ramakrishna, 2018; Kumar, 2018), paving the way for economic sustainability (Kiel et al., 2017). Time is an invaluable resource in the manufacturing economics, and the decentralization, horizontal/vertical integration, interoperability and real-time capability of

Table 2
Results of content analysis of key journal articles on Industry 4.0 sustainability functions.

No	Researcher	Functions															
		BMNI	CGER	CPI	ECD	ERS	EVRD	HRD	IPEP	JBC	MCR	MGAF	PDM	PRP	RSM	SCDI	SWE
1	Ardito et al. (2019)															x	
2	Barata et al. (2018)															x	
3	Braccini and Margherita (2019)		x		x	x	x			x	x						x
4	Batista et al. (2017)					x											x
5	Bechtsis et al. (2018)					x	x										
6	Beier et al. (2017)					x	x			x					x		
7	Beier et al. (2018)					x	x									x	
8	Branger and Pang (2015)		x			x				x				x	x		x
9	Buer et al. (2018)					x	x				x	x					
10	Cezarino et al. (2019)				x												x
11	Chen et al. (2017)								x				x				
12	Dalenogare et al. (2018)	x				x		x	x		x			x	x		
13	Davis et al. (2012)			x	x			x		x	x				x	x	
14	Faheem et al. (2018)		x			x									x		
15	Fatorachian and Kazemi (2018)					x			x			x		x		x	
16	Fettermann et al. (2018)					x			x						x		
17	Ford and Despeisse (2016)	x	x	x		x	x		x		x	x	x	x			
18	Frey and Osborne (2017)									x							
19	Gavish et al. (2015)							x									
20	Ghobakhloo (2018)	x			x		x	x	x	x	x		x	x		x	x
21	Ghobakhloo et al. (2018b)		x	x		x	x	x	x		x					x	
22	Ghobakhloo (2019)		x										x	x	x	x	
23	Ghobakhloo and Fathi (2019)		x	x		x	x	x	x	x		x			x	x	
24	Gupta (2019)												x				
25	Hahn (2019)							x							x		
26	Hofmann and Rüsch (2017)					x			x							x	
27	Hongyu (2019)						x		x							x	
28	Huang et al. (2017)					x											
29	Ivanov et al. (2019)											x			x	x	
30	Jabbour et al. (2018a)				x											x	
31	Jabbour et al. (2018b)					x	x										
32	Junior et al. (2018)		x			x									x		
33	Kache and Seuring (2017)							x	x			x			x	x	
34	Kamble et al. (2019)			x			x	x	x								
35	Kamble et al. (2018)				x	x	x								x		
36	Kang et al. (2016)					x		x	x		x			x	x		
37	Kiel et al. (2017)	x		x				x					x				
38	Kusiak (2018)		x		x	x				x				x			x
39	Kusiak (2019)				x	x	x										x
40	Lin et al. (2018)				x												
41	Lin et al. (2017)				x												x
42	Longo et al. (2017)							x									
43	Moeuf et al. (2018)			x							x	x					
44	Mohamed et al. (2019)					x					x						
45	Müller and Voigt (2018c)	x				x		x	x					x			
46	Müller et al. (2018a)	x		x				x	x		x	x		x		x	
47	Müller et al. (2018b)	x		x		x			x		x						x
48	Müller et al. (2019)								x			x			x	x	
49	Nascimento et al. (2019)					x	x										
50	Niaki et al. (2019)					x					x		x				
51	Oesterreich and Teuteberg (2016)		x			x									x	x	
52	Qi and Tao (2018)												x		x		
53	Qu et al. (2019)	x							x		x				x	x	
54	Reis and Gins (2017)														x		
55	Sisinni et al. (2018)					x									x		
56	Singh et al. (2019)															x	
57	Sivathanu and Pillai (2018)							x									
58	Sony and Naik (2019)														x	x	
59	Strandhagen et al. (2017)								x				x	x			
60	Strange and Zucchella (2017)															x	
61	Sung (2018)	x															
62	Szalavetz (2019)			x					x		x						
63	Tao et al. (2018a)	x					x						x				
64	Tao et al. (2018b)								x		x			x	x		
65	Telukdarie et al. (2018)			x					x						x		
66	Tortorella and Fettermann (2018)			x		x			x								
67	Upadhyay and Khandelwal (2018)							x									
68	Wang et al. (2017)								x		x		x	x			
69	Xu et al. (2018)	x							x								x
70	Yang et al. (2017)								x		x	x	x	x			
71	Yin et al. (2018)			x		x			x		x		x	x			
72	Zheng et al. (2018)					x			x					x	x		

Note: Business model novelty and innovation, BMNI; Carbon/harmful gas emission reduction, CGER; Corporate profitability improvement, CPI; Economic development, ECD; Energy and resource sustainability, ERS; Environmental responsibility development, EVRD; Human resource development, HRD; Increased production efficiency and productivity, IPEP; Job creation, JBC; Manufacturing cost reduction, MCR; Manufacturing agility and flexibility, MGAF; Production modularity, PDM; Product personalization, PRP; Risk and safety management, RSM; Supply chain digitization and integration, SCDI; Social welfare enhancement, SWE.

Industry 4.0 have numerous time efficiency implications, for example in terms of manufacturing cycle time or procurement lead time efficiency (Ardito et al., 2019; Dalenogare et al., 2018).

3.1.6. Environmental responsibility development

Industrial 4.0 and the digitization of the manufacturing sector offer profound implications for socio-economic sustainability thanks to the development of reactive and proactive environmental-friendly practices (Kamble et al., 2018). Additive manufacturing technologies, AVR, and HPC-CADM, for example, facilitate the development of new environmental-friendly products (Ford and Despeisse, 2016; Niaki et al., 2019). Environmental management practices such as life cycle assessment, Eco Balance, or environmental performance benchmarking are extremely information-intensive, and the data and information integration, sharing, and management capabilities of IIoT, IoS, and cloud big data facilitate the value-network-wide development of environmental management capabilities (Gbededo et al., 2018; Khuntia et al., 2018). Viewed from the lens of economic sustainability, the digital transition would allow businesses to capture market intelligence and further sense and absorb environmental sustainability opportunities (Jabbour et al., 2018b). More importantly, the productivity impact of Industry 4.0 enabled by collaborative production management, supply chain-wide knowledge management capabilities, production flexibility, and design modularity offer various environmental sustainability opportunities in terms of waste reduction and material efficiency (Kiel et al., 2017; Niaki et al., 2019).

3.1.7. Human resource development

Industry 4.0 and digital transformation are fundamentally reshaping the ways of working for human resources (Longo et al., 2017). Experts believe process simplification and automation, and the resulting enhanced decision-making can significantly boost human resource efficiency (Sivathanu and Pillai, 2018). AI and data analytics tools, for example, can enable managers to extract meaningful patterns from the employee data and offer personalized career development schemes or learning programs based on the behaviour, experience, skills, personality, and learning patterns of each employee (Stone et al., 2018). The use of IoP in the corporate context, which is commonly referred to as social intranets, allows employees and managers to more freely and interactively communicate with each other, reducing the communication gap among the leadership, middle-management, and employees (De Zubielqui et al., 2019). More importantly, visual and simulation technologies such as AVR offers one the most effective ways of industrial training (Martín-Gutiérrez et al., 2015). Overall, AVR offers a more affordable, safer, quicker, and productive learning experience. Maintenance personnel, for example, can safely practice dangerous or sensitive repairs and improve their readiness before committing to them (Gavish et al., 2015). Organizations can also implement AI and predictive analytics to scrutinize the history of a specific job position and identify the most suitable candidates having required competencies among the pool of existing talents (Karatop et al., 2015; Stone et al., 2018; Upadhyay and Khandelwal, 2018). Digitally-enabled human resource development initiatives, in turn, offer numerous socioeconomic sustainability opportunities such as employee productivity and overall corporate efficiency.

3.1.8. Increased production efficiency and productivity

The production efficiency and productivity impacts of Industry 4.0 are well-documented (Buer et al., 2018; Tortorella and Fettermann, 2018). Manufacturing digitization in Industry 4.0 setting allows manufacturers to develop and implement the hybrid lean-agile manufacturing ecosystem in support of product personalization philosophy (Ghobakhloo and Azar, 2018). The asynchronous manufacturing capability of the lean-agile manufacturing system would, in turn, allow the mass-production-capable production facilities to profitably satisfy the ever-changing customer demands, even via small lot or even single item production (Venugopal and Saleeshya, 2019). Alternatively, the automation, interoperability, and intelligence of CPPS contribute to production efficiency and productivity by improving process control measures, facilitating real-time maintenance, monitoring machine performance in real-time, increasing scheduling efficiency, and reducing machine downtime (Lee et al., 2015; Reis and Gins, 2017). More importantly, industrial automation reduces human intervention, which leads to lower human errors, reduced risk, and safety concerns (Chen et al., 2017; Lu and Weng, 2018).

3.1.9. Job creation

Industrial reports indicate that Industry 4.0 has had a significant impact on the recruitment industry (Brougham and Haar, 2018; Sung, 2018). In the Industry 4.0 environment, industrial robots, automated vehicles, and intelligent machines are replacing humans in numerous activities such as inventory tracking, quality control, and even product distribution (Frey and Osborne, 2017; Zheng et al., 2018). Experts expect Industry 4.0 to eliminate a significant portion of low to medium-skilled jobs but offset the automation-related job loss by creating numerous new employment opportunities in the area of informatics, mechatronics, process engineering, and system integration (Ghobakhloo and Fathi, 2019). The social sustainability implications of Industry 4.0 are not merely limited to the creation of digitization-related employment opportunities. Industry 4.0 and the digitization of the manufacturing industry contribute to the greener and more sustainable economy leading to the creation of millions of sustainable manufacturing-related job opportunities.

3.1.10. Manufacturing cost reduction

The cost-saving advantages that Industry 4.0 offers to the manufacturing industry is well-discussed (Moeuf et al., 2018; Schroeder et al., 2019). The autonomous 24/7 non-stop production, improved process controllability, improve manufacturing precision and quality, real-time monitoring and accident prevention, maintenance efficiency, higher equipment effectiveness, lower human errors, quality decision-making, streamlined procurement processes, reduced human resource costs, and material/resource/energy efficiency are examples of Industry 4.0 implications for manufacturing cost reduction (Dalenogare et al., 2018; Fatorachian and Kazemi, 2018; Fettermann et al., 2018; Lin et al., 2018).

3.1.11. Manufacturing agility and flexibility

Manufacturers nowadays are facing demand uncertainties, product individualization demands, and reduced lifespan of products and manufacturing technologies (Lasi et al., 2014). Under such circumstances, Industry 4.0 contributes to corporate sustainability by enabling manufacturers to develop a more agile and flexible manufacturing system (Brettel et al., 2016). Nextgen intelligent Enterprise Resource Planning (ERP), industrial simulation, digital twins, and big data analytics allow the business to deal with environmental uncertainties efficiently, and micromanage change processes or transform their existing business model(s) in the turbulent business environment as economically and promptly as possible (Kusiak, 2018; Yin et al., 2018). Alternatively, the vertical integration, real-time capability, and interoperability features of

Industry 4.0 enable manufacturers to reduce the costs of production and process adjustment decisions (Ivanov et al., 2019). More importantly, the digitally enabled virtual intimacy and the cloud-based connection across value chains, smart production lines, and decentralization in the Industry 4.0 context would create an agile manufacturing eco-system that enables fast reaction and adaptation capacities in response to the change and environmental uncertainties (Singh et al., 2019).

3.1.12. Production modularity

Industry 4.0 and the underlying smart digital technologies can support sustainability by enabling manufacturers to embrace a modular approach to product design, engineering, manufacturing, and delivery (Åkerman et al., 2018). AVR and HPC-CADM, coupled with the digitally-enabled virtual New Product Development (NPD) collaboration across supply networks, would significantly improve product design modularity (Kubota et al., 2017; Marion et al., 2015). The modular product design, in turn, offers advantages such as shorter time to market, reduced production complexity and costs, higher product quality, longer product lifespan, and material and resource efficiency (Piran et al., 2017; Ülkü and Hsuan, 2017). The favorable presence of IIoT, CPPS, and the interoperability feature would allow the physical modularization of production equipment, facilities, or even the entire production networks, conditions that enable production facilities to be easily converted and used for alternative products or processes without high reengineering or re-automation costs (Åkerman et al., 2018). Higher productivity, better process stability, product customizability, and reduced waste and lead-times are among other sustainability opportunities delivered by production modularization (Gupta, 2019; Shoval and Efatmaneshnik, 2019).

3.1.13. Product personalization

Industry 4.0 is offering novel opportunities for product personalization (Wang et al., 2017). Manufacturers nowadays can develop the production personalization strategy, which is the newest form of differentiation strategy, and stay competitive in the digitization era (Gu and Koren, 2018). The emergence of IoS, IoP, and data mining capabilities has enabled manufacturers to communicate and interact with the customer directly and collect and analyse enormous volume of data on customer preferences and consumption habits (Silva et al., 2017; Wang et al., 2017). The recent accessibility of additive manufacturing coupled with the production modularity feature of smart factories allows manufacturers to produce Ultra-Personalized Products (UPPs) based on consumer preferences and new ideas (Norman et al., 2017; Torn and Vaneker, 2019). Thanks to the emergence of reconfigurable mass production systems, customers can receive UPPs at a much more affordable price, and manufacturers can earn more value from each product unit (Gu and Koren, 2018; Yang et al., 2017). At the plant level, the application of digital twin models and AI-based production planning contribute to the optimum synchronization of the manufacturing practices and operations on various UPPs manufactured simultaneously (Leng et al., 2019; Tao et al., 2018a).

3.1.14. Risk and safety management

The risk management and anticipation implications of Industry 4.0 are multifaceted. The application of IIoT, Semantic technology, cloud data, and advanced analytics, and the resulting removal of information silos and the streamlined flow of information about inventory level, machine conditions, plant capacity, transportation routes, and procurement schedules will eventually lead to a greater End-to-End (E2E) visibility (Ardito et al., 2019; Kamble et al., 2019; Tang and Ghobakhloo, 2013). The data-driven E2E visibility, in turn, leads to the manufacturing risk reduction and stability improvement (Ivanov et al., 2019). Therefore, Industry 4.0 allows manufacturers to identify potential hazards in real-time and act upon them before they become real risks. In particular, tools such as intelligent cameras, smart sensors, smart safety wearables, and AI-based location awareness systems can detect and report any human or machine behaviour that might pose a risk to safety (Kamble et al., 2018; Reis and Gins, 2017). Besides, many of Industry 4.0-related technologies nowadays have the advanced built-in safety measures such as open SAFETY for the safe and reliable operation of production machinery. Industry 4.0-compatible technologies for maintenance management that allow real-time and autonomous assets troubleshooting and problem-solving reduce the safety concern of dynamic production environments significantly (Bragança et al., 2019; Li et al., 2017). Industry 4.0 has also been associated with the ever-increasing application of safer and more intelligent Collaborative Robots (cobots) in smart factories (Kim et al., 2019). Thanks to the advancements in AI, data analytics, and machine learning, the smarter cobots nowadays offer a better hazard identification and risk assessment capability (Cherubini et al., 2016). Smart cobots better interpret the world around them, involve reduced operation risk, and keep human co-workforce safer (Maurice et al., 2017; Schou et al., 2018).

3.1.15. Supply chain digitization and integration

The diffusion of technological innovations such as IIoT, cloud computing, Blockchain, and advanced analytics is transforming traditional supply chains into the DSN (Barata et al., 2018; Kache and Seuring, 2017). DSN includes three different functional layers. At the physical-digital layer, signals are collected via smart sensors, machine vision, and actuators across the value network. Machine and process controllers such as the programmable logic controller or supervisory control and data acquisition transform the signals captured from the physical world into meaningful digital records. At the digital-digital layer, AI and business analytics tools, which are embedded in the majority of modern ERP solutions, drive meaningful insights from the digital records. At the digital-physical layer, the AI-based decisions made based on the digital record are autonomously executed by physical assets across the supply network in real-time (Ardito et al., 2019; Ghobakhloo, 2019). The real-time, dynamic, integrative, intelligence, scalable, and agility features of DSNs offer numerous advantages such as supply chain-wide workload equality, higher operational efficiency, financial flow integration, ad-hoc dynamic planning, marketing effectiveness, collaborative planning, collaborative product design, and deeper customer integration (Dolgui et al., 2019). More importantly, and due to the better data acquisition and management, information integration, and physical process execution, DSNs can significantly prevent digital wastes (Bechtsis et al., 2018) and deliver competitive differentiation to the supply members (Ivanov et al., 2019).

3.1.16. Social welfare enhancement

During the past few decades, the advancement and diffusion of new technologies have not provided many opportunities for socioeconomic equality (Bauer, 2018). Existing economic reports and surveys reveal that technological advancements were somewhat associated with economic inequality, where new technologies offered more wealth and living standards to those who were more fortunate while others lagged behind even more drastically (Zhou and Tyers, 2018). Industry 4.0 and the new digitized manufacturing paradigm, however, can offer valuable opportunities for depolarisation of income and wealth (Branger and Pang, 2015; Xu et al., 2018). The countless employment opportunities and the increase of minimum wages due to skill-intensiveness of new jobs in the Industry 4.0 context can positively address the issue of economic inequality (Sung, 2018). Thanks to the product personalization design principle of Industry 4.0, even the most ordinary consumers can partially or entirely customize their orders without paying premium prices (Wang et al., 2017). The new marketing and distribution models, as well as the material, resources, and production efficiency offered by smart-digitized manufacturing is expected to enhance the global accessibility and affordability of goods and services (Strange and Zucchella, 2017). Business model innovation within the Industry 4.0 context, PaaS model, in particular, is reshaping the concept of ownership by lowering the importance of valuable possessions and easing the affordability of goods at the time of need (Jabbour et al., 2018a).

3.2. Establishing contextual relationships

To establish and identify the direction of the relationship among each pair of variables, the ISM technique uses the following symbols (Warfield, 1982):

V: Function i determines function j;
A: Function i is determined by function j;
X: Functions i and j determine each other;
O: Functions i and j are unrelated.

Establishing contextual relationships among the sustainability functions through capturing the opinions of the ten experts during NGT sessions leads to the development of the Structural Self-Interaction Matrix (SSIM), as presented in Table 3.

3.3. Establishing the initial reachability matrix

Table 4 offers the Initial Reachability Matrix (IRM) of this study. The IRM is a binary matrix that is established by replacing V, A, X, O symbols in the SSIM with 1 or 0 values under the following replacement rules (Govindan et al., 2015; Kaswan and Rathi, 2019):

-If the (i,j) entry in the SSIM is V, then entry (i,j) in the reachability matrix is set to 1, while entry (j,i) is set to 0.
-If the (i,j) entry in the SSIM is A, then entry (i,j) in the reachability matrix is set to 0, while entry (j,i) is set to 1.
-If the (i,j) entry in the SSIM is X, then both (i,j) and (j,i) entries in the reachability matrix are set to 1.
-If the (i,j) entry in the SSIM is 0, then in the reachability matrix both entry (i,j) and (j,i) are set to 0.

3.4. Establishing the final reachability matrix

The Final Reachability Matrix (FRM) is developed by subjecting the interrelationships within the IRM to the transitivity property (Dev and Shankar, 2016; Thirupathi and Vinodh, 2016). Table 5 presents the FRM of this study. The transitivity of contextual relations is an underlying assumption of the ISM technique, which assumes that if function A determines function B and function B determines function C, then function A necessarily determines function C (Fathi et al., 2019). For example, the BNMI function in the IRM (Table 3) does not determine EVARD. However, BNMI determines CPI, and CPI determines EVARD. Therefore, the entry (BNMI, EVARD) in the FRM (Table 5) becomes 1.

3.5. Establishing the hierarchy level of functions

The hierarchy level for Industry 4.0 sustainability functions in this study is developed using the reachability, antecedent, intersection sets for each of the functions established based on the values from the FRM (Warfield, 1982). The reachability set for a function includes the function itself as well as other functions that it determines (Raut and Gardas, 2018). The antecedent set for a function consists of the function itself and other functions that determine it (Govindan et al., 2015). The intersection set for each function consists of the intersection among the pair of reachability and the antecedent sets for that particular function (Fathi et al., 2019). After developing the reachability, antecedent, and intersection sets for all functions, the extraction process can be applied. In each iteration, the functions with the identical reachability and intersection sets are extracted. While disregarding the extracted functions within the previous iteration(s), this procedure is repeated, and the hierarchic levels of remaining functions are iteratively established. The hierarchy levels of Industry 4.0 sustainability functions are presented in Table A1 (Appendix).

3.6. Modelling contextual relationships

Fig. 4 represents the ISM model of Industry 4.0 functions for sustainability, which is developed based on the extraction levels identified in Table A1. This figure has been developed by

Table 3
The SSIM for sustainability functions of Industry 4.0.

Factors	SWE	SCDI	RSM	PRP	PDM	MGAF	MCR	JBC	IPEP	HRD	EVRD	ERS	ECD	CPI	CGER	BMNI
BMNI	V	A	O	V	A	A	O	V	O	O	O	V	V	V	V	–
CGER	O	A	A	A	O	A	O	O	A	O	A	A	A	X	–	
CPI	V	A	A	A	A	A	A	V	A	A	X	A	V	–		
ECD	O	O	O	O	O	A	A	X	O	O	A	A	–			
ERS	O	A	O	O	A	O	O	O	X	O	X	–				
EVRD	V	A	X	O	O	A	A	O	A	A	–					
HRD	O	V	V	O	V	V	V	O	V	–						
IPEP	O	A	A	O	A	A	V	O	–							
JBC	V	A	O	O	A	O	O	–								
MCR	V	A	A	V	A	A	–									
MGAF	O	A	A	V	A	–										
PDM	O	A	O	V	–											
PRP	V	A	O	–												
RSM	O	A	–													
SCDI	O	–														
SWE	–															

Table 4
IRM for sustainability functions of Industry 4.0.

Factors	BMNI	CGER	CPI	ECD	ERS	EVRD	HRD	IPEP	JBC	MCR	MGAF	PDM	PRP	RSM	SCDI	SWE
BMNI	1	1	1	1	1	0	0	0	1	0	0	0	1	0	0	1
CGER	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
CPI	0	1	1	1	0	1	0	0	1	0	0	0	0	0	0	1
ECD	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0
ERS	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
EVRD	0	1	1	1	1	1	0	0	0	0	0	0	0	1	0	1
HRD	0	0	0	0	0	1	1	1	0	1	1	1	0	1	1	0
IPEP	0	1	1	0	1	1	0	1	0	1	0	0	0	0	0	0
JBC	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1
MCR	0	0	1	1	0	1	0	0	0	1	0	0	1	0	0	1
MGAF	1	1	1	1	0	1	0	1	0	1	1	0	1	0	0	0
PDM	1	0	1	0	1	0	0	1	1	1	1	1	1	0	0	0
PRP	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1
RSM	0	1	1	0	0	1	0	1	0	1	1	0	0	1	0	0
SCDI	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0
SWE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 5
The final FRM with driving power and dependence level.

Factors	BMNI	CGER	CPI	ECD	ERS	EVRD	HRD	IPEP	JBC	MCR	MGAF	PDM	PRP	RSM	SCDI	SWE	*Driving Power*	Ranking
BMNI	1	1	1	1	1	1*	0	1*	1	0	0	0	1	0	0	1	*10*	**5**
CGER	0	1	1	1*	0	1*	0	0	1*	0	0	0	0	0	0	1*	*6*	**8**
CPI	0	1	1	1	1*	1	0	0	1	0	0	0	0	1*	0	1	*8*	**6**
ECD	0	1	1*	1	0	0	0	0	1	0	0	0	0	0	0	1*	*5*	**9**
ERS	0	1	1	1	1	1	0	1	1*	1*	0	0	0	1*	0	1*	*10*	**5**
EVRD	0	1	1	1	1	1	0	1*	1*	1*	1*	0	0	1	0	1	*11*	**4**
HRD	1*	1*	1*	1*	1*	1	1	1	1*	1	1	1	1*	1	1	1*	*16*	**1**
IPEP	0	1	1	1*	1	1	0	1	1*	1	0	0	1*	1*	0	1*	*11*	**4**
JBC	0	1*	0	1	0	0	0	0	1	0	0	0	0	0	0	1	*4*	**10**
MCR	0	1*	1	1	1*	1	0	0	1*	1	0	0	1	1*	0	1	*10*	**5**
MGAF	1	1	1	1	1*	1	0	1	1*	1	1	0	1	1*	0	1*	*13*	**3**
PDM	1	1*	1	1*	1	1*	0	1	1	1	1	1	1	0	0	1*	*13*	**3**
PRP	0	1	1	1*	0	1*	0	0	1*	0	0	0	1	0	0	1	*7*	**7**
RSM	1*	1	1	1*	1*	1	0	1	1*	1	1	0	1*	1	0	1*	*13*	**3**
SCDI	1	1	1	1*	1	1	0	1	1	1	1	1	1	1	1	1*	*15*	**2**
SWE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	*1*	**11**
Dependence Power	*6*	*15*	*14*	*15*	*11*	*13*	*1*	*9*	*15*	*9*	*6*	*3*	*9*	*9*	*2*	*16*		
Ranking	**7**	**2**	**3**	**2**	**5**	**4**	**10**	**6**	**2**	**6**	**7**	**8**	**6**	**6**	**9**	**1**		

positioning the 16 sustainability functions based on their hierarchical properties identified in iterations 1 to 11 (Table A1), representing the contextual relationships between functions as vector arrows, and eliminating the transitivities among them (Dev and Shankar, 2016; Govindan et al., 2015). Fig. 4 consists of 11 placement (precedence) levels that are consistent with the 11 iteration levels established in Table A1. The placement level in Fig. 4 is the opposite of the iteration level in Table A1, meaning functions extracted in the 11th iteration within Table A1 should be granted with the 1st placement level in Fig. 4. Therefore, human resource development extracted in iteration 11 is placed at the bottom (starting point) of the ISM model representing contextual relationships among Industry 4.0 functions.

4. Discussion

This research drew on the ISM technique for identifying the sustainability functions of Industry 4.0, capturing opinions of the expert group, and mapping the contextual relationships among the sustainability functions. The state-of-the-art content-driven review and analysis of the literature identified 16 different sustainability functions for Industry 4.0, and the ISM technique revealed that sophisticated precedence relationships exist among these functions. The model of Industry 4.0 sustainability functions in Fig. 4 explains that human resource development (HRM function) is the stepping stone for the development of other sustainability functions of Industry 4.0. The human resource development feature of Industry 4.0 leverages modern digital innovations such as AVR, IIoT, and simulation to facilitate the digitization and integration of the supply chain (SCDI function), given supply chain integration is an extremely skill-intensive process. SCDI function, in turn, enables production modularity (MGAF function), given MGAF is supported by various features of supply chain process integration such as virtual NPD collaboration, information sharing, and physical flow integration across supply partners. The modular design of products and modularity of production equipment further results in the manufacturing agility and flexibility (MGAF function), and risk and safety management (RSM function), the features that are vital to the development of more innovative business models such as MaaS and PaaS (BMNI function). The combination of new business model innovation (BMNI function), and manufacturing process streamlining-related sustainability functions (MGAF and RSM functions) offers massive opportunities for higher production efficiency and productivity across the manufacturing supply chains

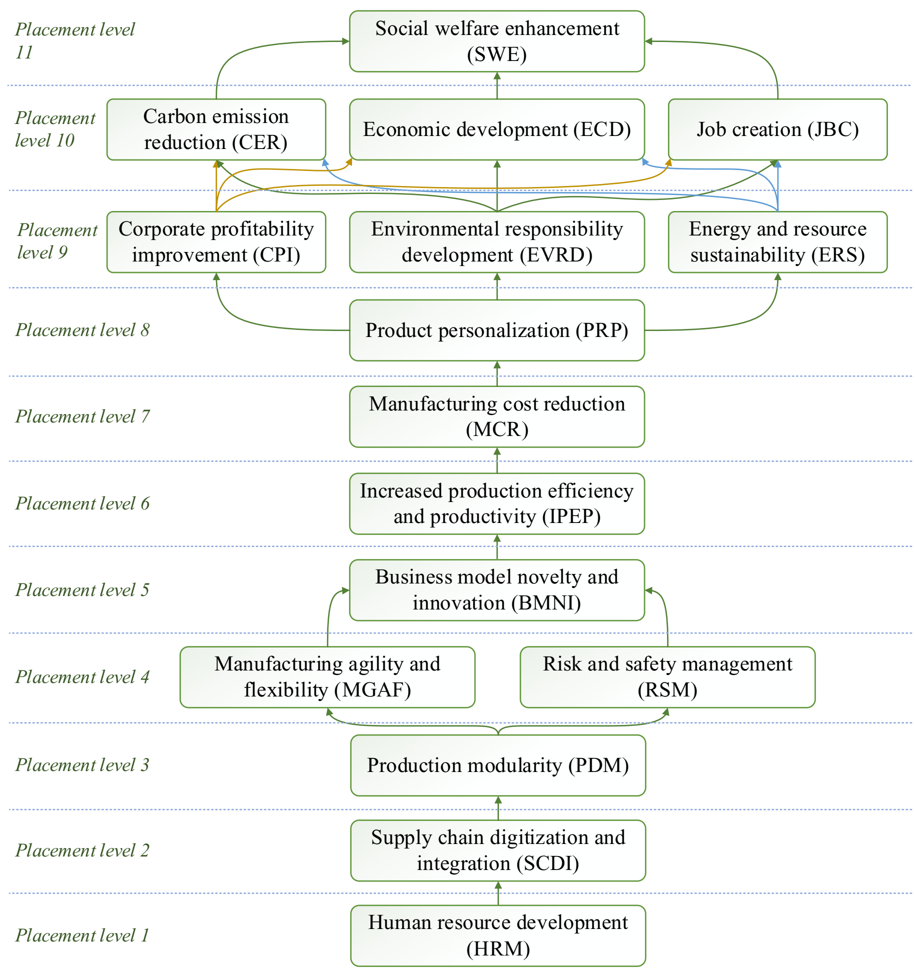

Fig. 4. The ISM model of Industry 4.0 functions for sustainability.

(IPEP function). The vertical integration, real-time capability, and interoperability features of the digitized manufacturing system and the resulting production efficiency and productivity, in turn, enable manufacturers to reduce the costs of production and process adjustment decisions (MCR function). Industry 4.0 cost-savings benefits for manufacturing lead directly to production personalization (PRP function).

The lower part of the ISM-based model in Fig. 4 explains how manufacturing digitization in Industry 4.0 transforms the entire value chain and enables manufacturers to expand their portfolio to include innovative business models. The structured and streamlined exchange of information across DSN, the possibilities for dynamic value configurations thanks to the production modularity, and manufacturing efficiency and cost reduction would enable manufacturers to profitably personalize their products and services and better meet customer expectations, the sustainability function that directly facilitates the three sustainability functions of corporate profitability improvement (CPI function), energy and resource sustainability (ERS function), and environmental responsibility development (EVRD function). The CPI, ERS, and EVRD sustainability functions, positioned at the 9th placement level in Fig. 4, further facilitate the development of three sustainability functions of carbon/harmful gas emission reduction (GER function), economic development (ECD function), and job creation (JBC function). Finally, yet importantly, the development of the sustainability function of social welfare enhancement (SWE function), positioned at the last placement level, is a direct result of the development of other sustainability functions of Industry 4.0 positioned at placement levels one to ten in Fig. 4.

4.1. MICMAC analysis

MICMAC analysis refers to the cross-multiplication impact matrix applied to a ranking, which enables identifying and analysing the driving power and the dependence power of the essential attributes of an interpretive model (Panahifar et al., 2014). MICMAC is an indirect classification technique for comparatively analysing the relational scope of each attribute (Fathi et al., 2019). Consistently, performing MICMAC analysis and identifying the dependence power and driving power of each sustainability function is the final step of ISM (Lim et al., 2017; Raut and Gardas, 2018). MICMAC in this study involves clustering Industry 4.0 sustainability functions identified in the following four categories based on their dependence and driving power values in the FRM (Fathi et al., 2019; Wang et al., 2018):

(I) Autonomous category consisting of sustainability functions with weak driving power and weak dependence; (II) Driver

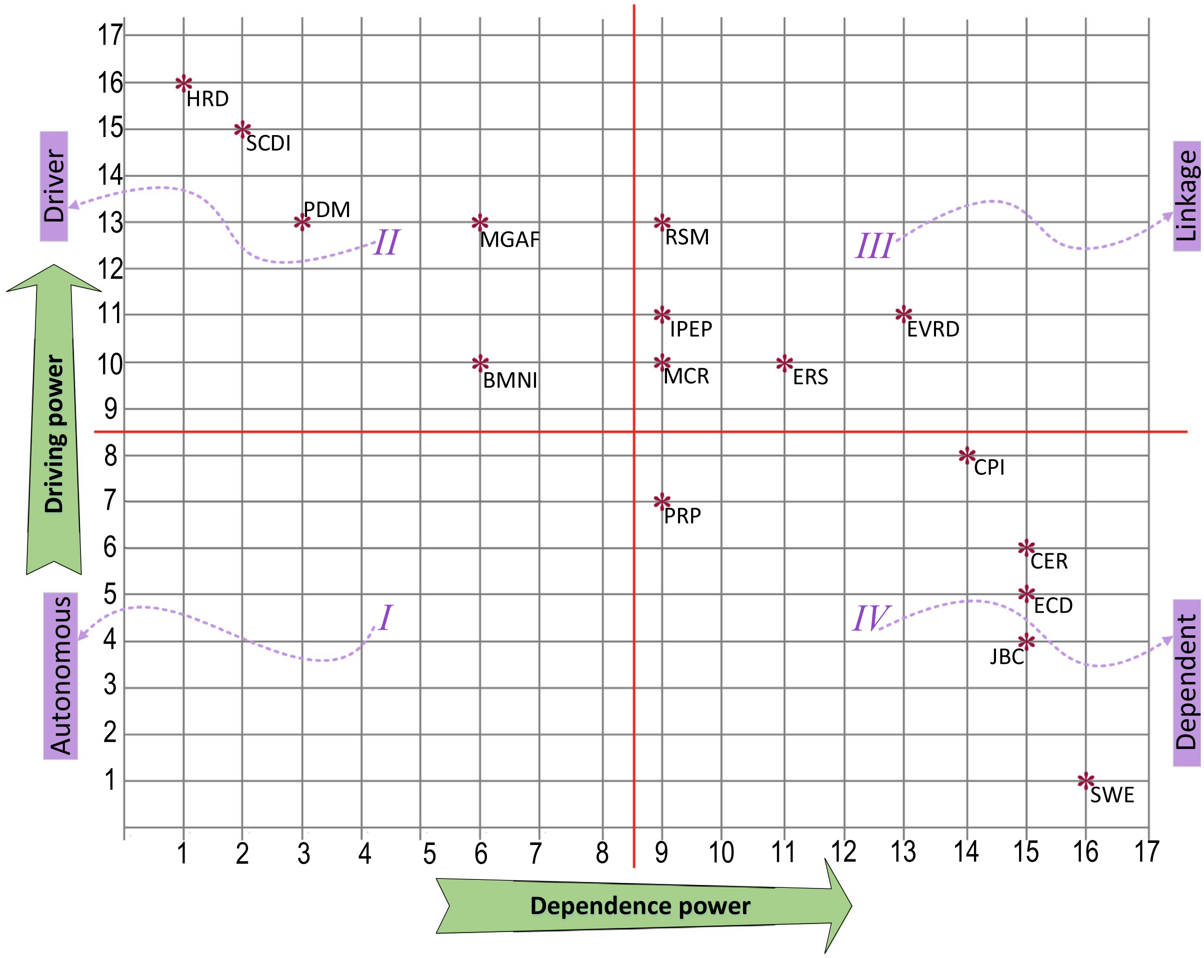

Fig. 5. Driving power and dependence diagram for sustainability functions of Industry 4.0.

cluster consisting of sustainability functions with strong driving power but weak dependence.

(III) Linkage cluster including sustainability functions with strong driving power and strong dependence; and (IV) Dependent category including sustainability functions with weak driving power but strong dependence;

Fig. 5 presents the driving power and dependence diagram for the sustainability functions of Industry 4.0. This diagram has been developed using power and dependence values calculated within the FRM and by positioning the sustainability functions into their appropriate quadrants. The lack of *autonomous* sustainability functions in this study is reminiscent of the sophisticated precedence relationships among sustainability functions of Industry 4.0. Fig. 5 explains that human resource development, supply chain digitization and integration, production modularity, manufacturing agility and flexibility, and business model novelty and innovation, as *driver* sustainability functions, are respectively the more immediate opportunities offered by Industry 4.0 for sustainability. Sustainability functions placed at the driver category are the critical enablers of other sustainability functions of Industry 4.0. Risk and safety management, increased production efficiency and productivity, manufacturing cost reduction, energy and resource sustainability, and environmental responsibility development, positioned at the top-right quadrant of the diagram, are categorized as the *linkage* sustainability functions, given they link the driver category to the dependent category. The linkage sustainability functions are the intermediate opportunities offered by Industry 4.0 to sustainability development. Product personalization, corporate profitability improvement, carbon/harmful gas emission reduction, economic development, job creation, and finally, social welfare enhancement, fall within the *dependent* category, which means they are the most remote opportunities that Industry 4.0 might offer to sustainability development, given they significantly depend on the presence of other sustainability functions from linkage and driver categories.

5. Conclusion, implications, and future directions

While some communities might still be in denial regarding the magnitude and importance of Industry 4.0, leading organizations have been implementing advanced digital technologies such as IIoT, AVR, industrial robotics, cloud computing, AI, and HPC-CADM in preparation for the rise of the new digital industrial revolution. Scholars and industrialists believe that Industry 4.0 may positively impact sustainability, and the present study attempted to provide an interpretive model of Industry 4.0 sustainability function explaining the processes through which the industrial digitization and the underlying technology trends and design principles can contribute to the achievement of economic, environmental, and social sustainability development goals.

5.1. Implications

Academia believes that Industry 4.0 and the underlying industrial digitization may offer opportunities for sustainability, such as resource efficiency or overall economic development. Nonetheless, these are the remote contributions of Industry 4.0 to sustainability. The digital transformation initiated by Industry 4.0 should first come to maturity to deliver its desired sustainability functions, and the development of human resources for digitization is the stepping stone for this process. Nowadays, the skills gaps across all industries are growing at an unprecedented rate, which is due to the snowballing deployment of advanced digital technologies, rapid advances in AI, and IIoT integration across various industries. This continuous trajectory is rapidly altering the very nature of the jobs, shrinking the low skill job opportunities and increasingly demanding technical skills in the areas of problem-solving, programming, creative thinking, and system design. The good news is, the same digital technologies responsible for the digitization skills gap can contribute to bridging it. The use of AVR, smart apps, IIoT-enabled information sharing, and data analytics tools can significantly improve the effectiveness of on-the-job training, talent screening and acquisition, learning programs, and career development schemes. Industry 4.0 further contributes to sustainability by digitizing supply chains and promoting integration across value networks. DSN, the combination of smart suppliers, connected customers, and smart factories coupled with the application of cognitive planning, additive manufacturing, sensor-driven replenishment, and AI-based decision-making, lead to a modular, flexible, agile, controlled, and secure value creation and delivery ecosystem. This ecosystem further enables innovative product and service personalization business models and minimizes inefficiencies, wastes, and non-value-added activities. The innovative transformation of business models and processes and resulting efficiencies, in turn, offer numerous advantages such as corporate profitability, more affordable products and services, improved consumer experience, and enhanced customer lifetime value.

Manufacturing-economic sustainability is among the more immediate sustainability outcomes that Industry 4.0 may offer. The manufacturing-economic sustainability functions of Industry 4.0, when successfully delivered, can pave the way for the further contribution of Industry 4.0 to the environmental and socio-economic sustainability. In particular, the manufacturing efficiency, cost-saving, and corporate profitability functions of the digital transformation of the manufacturing industry enable the development of environmental management and energy/resource efficiency capabilities across manufacturing clusters and distribution channels, which eventually promote environmental protection and emission reduction. In particular, industrial digitization will reduce the cost and complexity of waste and emissions reduction, material efficiency, and energy sustainability across various manufacturing processes. Digitization will also enable manufacturers to analyse consumer behaviour in real-time and perform the advanced impact assessment of their products during and after their life cycle. Figs. 4 and 5 collectively imply that socio-economic sustainability functions are the most remote sustainability opportunities that Industry 4.0 may offer. The overall economic development functions of Industry 4.0 gravely rely on digital integration of supply members, business model innovation, corporate competitiveness and financial sustainability, manufacturing productivity and efficiency, energy efficiency, and human resource skill development. The consequent economic growth leads to more substantial demands across the labour market, higher wages, improved workplace and working conditions, social stability, and economic equality.

5.2. Limitations and future research

Holding an optimistic view of Industry 4.0, the present study identified and explained the opportunities that Industry manufacturing digitization *might potentially* offer for sustainability. While Industry 4.0 can change the world positively, the disruptive force of digitization and underlying technologies, if left unintended, may negatively impact sustainability. Therefore, future research is invited to extend the present research by addressing the following issues that could not be addressed conceivably in this study:

- The modularity, flexibility, and agility of smart factories and the product personalization principle of manufacturing digitization in the Industry 4.0 era accelerate product cycles and expedite the rapid obsolescence of goods and services. This environmentally undesirable condition may lead to higher demands for energy and resources and eventually increased pollution and waste generation. Thanks to the advancement of digital technologies, the overall improved quality of life and the rapidly growing world population have led to the ever-increasing global raw materials and energy demand, potentially suppressing the efficiency impact of digitization. This condition calls for public policy and multilateral agreements for controlling the unforeseen environmental sustainability impacts of Industry 4.0 and industrial digitization.
- The potential inequality impacts of Industry 4.0 remains a significant concern. Although the World Economic Forum Global Risks Report indicates that Industry 4.0 and the underlying industrial digitization has the capacity to increase income levels and enhance the quality of life for all people, however, it cannot be ignored that billions of people still do not have the necessary access to clean drinking water, electricity, or safe sanitation, welfare systems long-developed during the second industrial revolution. The challenges of the digital manufacturing revolution arising from the massive cost of digitization, cybersecurity concerns, digitization maturity, and technology accessibility may cause the manufacturing digitization revolution to go hand in hand with temporary exclusivity based on first-mover advantage, mostly available to dominant mega-corporations in more developed countries. The resulting digital non-rivalry, in turn, may cause wealth disparities in the global consumer market.
- Communities with limited access to education and fewer skills, particularly in developing countries, might be at a disadvantage as Industry 4.0 progresses. To address the potential skills premium and job polarisation threats of Industry 4.0, companies and governments should devise educational equality strategies to address the issue of the skills gap intensified because of the impact of digital manufacturing innovation.

In sum, Industry 4.0 stakeholders, leaders in the public and private sectors, industrialists, and academicians, should work together to ensure that the sustainability opportunities of Industry 4.0 are distributed across communities and around the world as equally and fairly as possible.

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.

Appendices

Table A1
Hierarchy level for Industry 4.0 sustainability functions.

Factors	Reachability set	Antecedent set	Intersection set	Level
Iteration 1				
BMNI	BMNI, CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, PRP, SWE	BMNI, HRD, MGAF, PDM, RSM, SCDI	BMNI	
CGER	CGER, CPI, ECD, EVRD, JBC, SWE	BMNI, CGER, CPI, ECD, ERS, EVRD, HRD, IPEP, JBC, MCR, MGAF, PDM, PRP, RSM, SCDI	CGER, CPI, ECD, EVRD, JBC	
CPI	CGER, CPI, ECD, ERS, EVRD, JBC, RSM, SWE	BMNI, CGER, CPI, ECD, ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	CGER, CPI, ECD, ERS, EVRD, RSM	
ECD	CGER, CPI, ECD, JBC, SWE	BMNI, CGER, CPI, ECD, ERS, EVRD, HRD, IPEP, JBC, MCR, MGAF, PDM, PRP, RSM, SCDI	CGER, CPI, ECD, JBC	
ERS	CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, RSM, SWE	BMNI, CPI, ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, RSM, SCDI	CPI, ERS, EVRD, IPEP, MCR, RSM	
EVRD	CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, MGAF, RSM, SWE	BMNI, CGER, CPI, ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	CGER, CPI, ERS, EVRD, IPEP, MCR, MGAF, RSM	
HRD	BMNI, CGER, CPI, ECD, ERS, EVRD, HRD, IPEP, JBC, MCR, MGAF, PDM, PRP, RSM, SCDI, SWE	HRD	HRD	
IPEP	CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, PRP, RSM, SWE	BMNI, ERS, EVRD, HRD, IPEP, MGAF, PDM, RSM, SCDII	ERS, EVRD, IPEP, RSM	
JBC	CGER, ECD, JBC, SWE	BMNI, CGER, CPI, ECD, ERS, EVRD, HRD, IPEP, JBC, MCR, MGAF, PDM, PRP, RSM, SCDI	CGER, ECD, JBC	
MGCR	CGER, CPI, ECD, ERS, EVRD, JBC, MCR, PRP, RSM, SWE	ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, RSM, SCDI	ERS, EVRD, MCR, RSM	
MGAF	BMNI, CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, MGAF, PRP, RSM, SWE	EVRD, HRD, MGAF, PDM, RSM, SCDI	EVRD, MGAF, RSM	
PDM	BMNI, CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, MGAF, PDM, PRP, SWE	HRD, PDM, SCDI	PDM	
PRP	CGER, CPI, ECD, EVRD, JBC, PRP, SWE	BMNI, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	PRP	
RSM	BMNI, CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, MGAF, PRP, RSM, SWE	CPI, ERS, EVRD, HRD, IPEP, MCR, MGAF, RSM, SCDI	CPI, ERS, EVRD, IPEP, MCR, MGAF, RSM	
SCDI	BMNI, CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, MGAF, PDM, PRP, RSM, SCDI, SWE	HRD, SCDI	SCDI	
SWE	SWE	BMNI, CGER, CPI, ECD, ERS, EVRD, HRD, IPEP, JBC, MCR, MGAF, PDM, PRP, RSM, SCDI, SWE	SWE	*I*
Iteration II				
BMNI	BMNI, CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, PRP	BMNI, HRD, MGAF, PDM, RSM, SCDI	BMNI	
CGER	CGER, CPI, ECD, EVRD, JBC	BMNI, CGER, CPI, ECD, ERS, EVRD, HRD, IPEP, JBC, MCR, MGAF, PDM, PRP, RSM, SCDI	CGER, CPI, ECD, EVRD, JBC	*II*
CPI	CGER, CPI, ECD, ERS, EVRD, JBC, RSM	BMNI, CGER, CPI, ECD, ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	CGER, CPI, ECD, ERS, EVRD, RSM	
ECD	CGER, CPI, ECD, JBC	BMNI, CGER, CPI, ECD, ERS, EVRD, HRD, IPEP, JBC, MCR, MGAF, PDM, PRP, RSM, SCDI	CGER, CPI, ECD, JBC	*II*
ERS	CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, RSM	BMNI, CPI, ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, RSM, SCDI	CPI, ERS, EVRD, IPEP, MCR, RSM	
EVRD	CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, MGAF, RSM	BMNI, CGER, CPI, ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	CGER, CPI, ERS, EVRD, IPEP, MCR, MGAF, RSM	
HRD	BMNI, CGER, CPI, ECD, ERS, EVRD, HRD, IPEP, JBC, MCR, MGAF, PDM, PRP, RSM, SCDI	HRD	HRD	
IPEP	CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, PRP, RSM	BMNI, ERS, EVRD, HRD, IPEP, MGAF, PDM, RSM, SCDI	ERS, EVRD, IPEP, RSM	
JBC	CGER, ECD, JBC	BMNI, CGER, CPI, ECD, ERS, EVRD, HRD, IPEP, JBC, MCR, MGAF, PDM, PRP, RSM, SCDI	CGER, ECD, JBC	*II*
MCR	CGER, CPI, ECD, ERS, EVRD, JBC, MCR, PRP, RSM	ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, RSM, SCDI	ERS, EVRD, MCR, RSM	
MGAF	BMNI, CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, MGAF, PRP, RSM	EVRD, HRD, MGAF, PDM, RSM, SCDI	EVRD, MGAF, RSM	
PDM	BMNI, CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, MGAF, PDM, PRP	HRD, PDM, SCDI	PDM	
PRP	CGER, CPI, ECD, EVRD, JBC, PRP	BMNI, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	PRP	
RSM	BMNI, CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, MGAF, PRP, RSM	CPI, ERS, EVRD, HRD, IPEP, MCR, MGAF, RSM, SCDI	CPI, ERS, EVRD, IPEP, MCR, MGAF, RSM	
SCDI	BMNI, CGER, CPI, ECD, ERS, EVRD, IPEP, JBC, MCR, MGAF, PDM, PRP, RSM, SCDI	HRD, SCDI	SCDI	
Iteration III				
BMNI	BMNI, CPI, ERS, EVRD, IPEP, PRP	BMNI, HRD, MGAF, PDM, RSM, SCDI	BMNI	
CPI	CPI, ERS, EVRD, RSM	BMNI, CPI, ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	CPI, ERS, EVRD, RSM	*III*
ERS	CPI, ERS, EVRD, IPEP, MCR, RSM	BMNI, CPI, ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, RSM, SCDI	CPI, ERS, EVRD, IPEP, MCR, RSM	*III*
EVRD	CPI, ERS, EVRD, IPEP, MCR, MGAF, RSM	BMNI, CPI, ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	CPI, ERS, EVRD, IPEP, MCR, MGAF, RSM	*III*
HRD	BMNI, CPI, ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	HRD	HRD	
IPEP	CPI, ERS, EVRD, IPEP, MCR, PRP, RSM	BMNI, ERS, EVRD, HRD, IPEP, MGAF, PDM, RSM, SCDI	ERS, EVRD, IPEP, RSM	
MCR	CPI, ERS, EVRD, MCR, PRP, RSM	ERS, EVRD, HRD, IPEP, MCR, MGAF, PDM, RSM, SCDI	ERS, EVRD, MCR, RSM	
MGAF	BMNI, CPI, ERS, EVRD, IPEP, MCR, MGAF, PRP, RSM	EVRD, HRD, MGAF, PDM, RSM, SCDI	EVRD, MGAF, RSM	
PDM	BMNI, CPI, ERS, EVRD, IPEP, MCR, MGAF, PDM, PRP	HRD, PDM, SCDI	PDM	
PRP	CPI, EVRD, PRP	BMNI, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	PRP	

(*continued on next page*)

Table A1 (*continued*)

Factors	Reachability set	Antecedent set	Intersection set	Level
RSM	BMNI, CPI, ERS, EVRD, IPEP, MCR, MGAF, PRP, RSM	CPI, ERS, EVRD, HRD, IPEP, MCR, MGAF, RSM, SCDI	CPI, ERS, EVRD, IPEP, MCR, MGAF, RSM	
SCDI	BMNI, CPI, ERS, EVRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	HRD, SCDI	SCDI	
Iteration IV				
BMNI	BMNI, IPEP, PRP	BMNI, HRD, MGAF, PDM, RSM, SCDI	BMNI	
HRD	BMNI, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	HRD	HRD	
IPEP	IPEP, MCR, PRP, RSM	BMNI, HRD, IPEP, MGAF, PDM, RSM, SCDI	IPEP, RSM	
MCR	MCR, PRP, RSM	HRD, IPEP, MCR, MGAF, PDM, RSM, SCDI	MCR, RSM	
MGAF	BMNI, IPEP, MCR, MGAF, PRP, RSM	HRD, MGAF, PDM, RSM, SCDI	MGAF, RSM	
PDM	BMNI, IPEP, MCR, MGAF, PDM, PRP	HRD, PDM, SCDI	PDM	
PRP	PRP	BMNI, HRD, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	PRP	*IV*
RSM	BMNI, IPEP, MCR, MGAF, PRP, RSM	HRD, IPEP, MCR, MGAF, RSM, SCDI	IPEP, MCR, MGAF, RSM	
SCDI	BMNI, IPEP, MCR, MGAF, PDM, PRP, RSM, SCDI	HRD, SCDI	SCDI	
Iteration V				
BMNI	BMNI, IPEP	BMNI, HRD, MGAF, PDM, RSM, SCDI	BMNI	
HRD	BMNI, HRD, IPEP, MCR, MGAF, PDM, RSM, SCDI	HRD	HRD	
IPEP	IPEP, MCR, RSM	BMNI, HRD, IPEP, MGAF, PDM, RSM, SCDI	IPEP, RSM	
MCR	MCR, RSM	HRD, IPEP, MCR, MGAF, PDM, RSM, SCDI	MCR, RSM	*V*
MGAF	BMNI, IPEP, MCR, MGAF, RSM	HRD, MGAF, PDM, RSM, SCDI	MGAF, RSM	
PDM	BMNI, IPEP, MCR, MGAF, PDM	HRD, PDM, SCDI	PDM	
RSM	BMNI, IPEP, MCR, MGAF, RSM	HRD, IPEP, MCR, MGAF, RSM, SCDI	IPEP, MCR, MGAF, RSM	
SCDI	BMNI, IPEP, MCR, MGAF, PDM, RSM, SCDI	HRD, SCDI	SCDI	
Iteration VI				
BMNI	BMNI, IPEP	BMNI, HRD, MGAF, PDM, RSM, SCDI	BMNI	
HRD	BMNI, HRD, IPEP, MGAF, PDM, RSM, SCDI	HRD	HRD	
IPEP	IPEP, RSM	BMNI, HRD, IPEP, MGAF, PDM, RSM, SCDI	IPEP, RSM	*VI*
MGAF	BMNI, IPEP, MGAF, RSM	HRD, MGAF, PDM, RSM, SCDI	MGAF, RSM	
PDM	BMNI, IPEP, MGAF, PDM	HRD, PDM, SCDI	PDM	
RSM	BMNI, IPEP, MGAF, RSM	HRD, IPEP, MGAF, RSM, SCDI	IPEP, MGAF, RSM	
SCDI	BMNI, IPEP, MGAF, PDM, RSM, SCDI	HRD, SCDI	SCDI	
Iteration VII				
BMNI	BMNI	BMNI, HRD, MGAF, PDM, RSM, SCDI	BMNI	*VII*
HRD	BMNI, HRD, MGAF, PDM, RSM, SCDI	HRD	HRD	
MGAF	BMNI, MGAF, RSM	HRD, MGAF, PDM, RSM, SCDI	MGAF, RSM	
PDM	BMNI, MGAF, PDM	HRD, PDM, SCDI	PDM	
RSM	BMNI, MGAF, RSM	HRD, MGAF, RSM, SCDI	MGAF, RSM	
SCDI	BMNI, MGAF, PDM, RSM, SCDI	HRD, SCDI	SCDI	
Iteration VIII				
HRD	HRD, MGAF, PDM, RSM, SCDI	HRD	HRD	
MGAF	MGAF, RSM	HRD, MGAF, PDM, RSM, SCDI	MGAF, RSM	*VIII*
PDM	MGAF, PDM	HRD, PDM, SCDI	PDM	
RSM	MGAF, RSM	HRD, MGAF, RSM, SCDI	MGAF, RSM	*VIII*
SCDI	MGAF, PDM, RSM, SCDI	HRD, SCDI	SCDI	
Iteration IX				
HRD	HRD, PDM, SCDI	HRD	HRD	
PDM	PDM	HRD, PDM, SCDI	PDM	*IX*
SCDI	PDM, SCDI	HRD, SCDI	SCDI	
Iteration X				
HRD	HRD, SCDI	HRD	HRD	
SCDI	SCDI	HRD, SCDI	SCDI	*X*
Iteration XI				
HRD	HRD	HRD	HRD	*XI*

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Glossary

AGV: Automated Guided Vehicles
AI: Artificial Intelligence
AVR: Augmented and Virtual Reality
BMNI: Business Model Novelty and Innovation
CGER: Carbon/harmful Gas Emission Reduction
CPI: Corporate Profitability Improvement
CPPS: Cyber-Physical Production Systems
CSI: Crowd-Sourced Innovation
DSN: Digital Supply Network
E2E: End-to-End
ECD: Economic Development
ERP: Enterprise Resource Planning
ERS: Energy and Resource Sustainability
EVRD: Environmental Responsibility Development
FRM: Reachability Matrix
HPC-CADM: High-Performance Computing-powered Computer-Aided Design and Manufacturing
HRD: Human Resource Development
IDOT: Information, Digital, and Operation Technologies
IIoT: Industrial Internet of Things
IoP: Internet of People
IoS: Internet of Services
IPEP: Increased Production Efficiency and Productivity
IRM: Initial Reachability Matrix
ISM: Interpretive Structural Modelling
JBC: Job Creation
MaaS: Manufacturing as a Service
MCR: Manufacturing Cost Reduction
MGAF: Manufacturing Agility and Flexibility
MICMAC: Matrice d'Impacts Croisés Multiplication Appliquée àun Classement
NGT: Nominal Group Technique
NPD: New Product Development
PaaS: Product-as-a-Service
PDM: Production Modularity
PRP: Product Personalization
RSM: Risk and Safety Management
SCDI: Supply Chain Digitization and Integration
SSIM: Structural Self-Interaction Matrix
SWE: Social Welfare Enhancement
UPPs: Ultra-Personalized Products

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