

Industry 4.0 – challenges to implement circular economy

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Challenges to
implement CE

Abstract

Purpose – The purpose of this paper is to identify the Industry 4.0 barriers to achieve circular economy (CE). The study focuses on exploring the link between Industry 4.0 and CE. This leads to the implementation of integrated Industry 4.0-CE and attainment of sustainable production and consumption through analyzing the technological benefits of Industry 4.0.

Design/methodology/approach – Industry 4.0 barriers are identified from literature review and discussions with industry experts. Here, the interpretive structural modeling (ISM) technique is applied to develop the contextual relationship among the barriers and to identify the prominent barriers hindering the CE implementation.

Findings – The ISM hierarchical model and Matriced' impacts croised-multiplication applique' and classment analysis illustrate that the digitalization process and the semantic interoperability possess high driving power and low dependence. These barriers require keen attention to play a significant role in improving resource efficiency and sustainability, and absence of these barriers may not drive other barriers for CE. Apart from these barriers, cyber-physical systems standards and specifications, sensor technology and design challenges are also the most influential Industry 4.0 barriers for achieving CE.

Practical implications – The findings provide an opportunity for industry practitioners to explore the most driving Industry 4.0 barriers. The study confirms that integrated Industry 4.0-CE will maintain sustainable operations management by optimizing the production and consumption patterns. It will also provide an opportunity of customization where customers and products interact and can monitor the performance of the operations through the Internet of Things sensors.

Originality/value – The study provides integration of Industry 4.0 challenges to implement CE. However, the integration of the two burgeoning fields is still very scarce and lacks in adopting the technological benefits of the integrated Industry 4.0-CE.

Keywords ISM, Barriers, Circular economy, Industry 4.0, Industry 4.0-CE

Paper type Research paper

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1. Introduction

The fourth industrial revolution, i.e. Industry 4.0, was first introduced during the Hannover Messe, 2011 and officially declared as a German strategic initiative in 2013 to revolutionize the manufacturing industry (Xu *et al.*, 2018). It has gained momentum due to advancement in disruptive technologies through Internet of Things (IoT), big data, cloud computing and cyber-physical systems (CPS). Industry 4.0 has emerged as the promising technology to achieve efficiency, accuracy and precision. Previously, many studies have proposed the theoretical concept and deliverables of the Industry 4.0 implementation. These studies have suggested that the technologies enable data operations, improve efficiency and reduce energy wastages from the manufacturing process (Nascimento *et al.*, 2018). The physical world and the virtual world are connected through Industry 4.0 and, as a consequence, human-machine interaction takes place. This enables products, components and smart factory to form a communication network in order to be self-adapt and self-managed accordingly (Jabbour *et al.*, 2018). The aspects of Industry 4.0 lie in monitoring, interoperability, controlling, real-time information processing and self-optimizing the manufacturing process smartly such as customization, energy consumption, flexibility and forward-backward flow of materials.

Traditionally, manufacturing industries have put efforts in enhancing sustainable production and consumption in a linear supply chain that involved only the decisions of



vertically integrated systems, but the implementation of such sustainable networks was never been fruitful for the industries. Several existing studies have also argued for finding the new directions for economic development to deal with closed-loop supply chain, i.e. circular economy (CE). The concept of CE has evolved as a new way of sustainability and has gained popularity in resource scarcity, circulation of materials and facilitating the reuse and recycle paradigm. Consequently, due to consumer lifestyles, dynamic growth in manufacturing industries, carbon emissions and waste generation have become increasingly severe (Michael and Amir, 2016). The CE has a different perspective of production and consumption in restoring the value of the disposed products (Geissdoerfer *et al.*, 2017). The CE follows the circular approach and provides environmental, social and economic benefits to the organization when they replace the linear economy, i.e. take–make–dispose (Leider *et al.*, 2017). Previous studies on CE have emphasized on material flow in closed loop and the emerging technology advancements, but, due to the knowledge gap in integrating disruptive technology as well as lack of technological analysis, it leads to havoc in gaining CE (Jawahir and Bradley, 2016). These issues prevent the optimization of sustainability and lead to a question whether these advancing technologies can provide appropriate solutions to the manufacturing industry (Pagoropoulos *et al.*, 2017). The CE follows cradle-to-cradle approach and consists of recycling, reusability and remanufacturing. On the basis of this approach, reverse supply chain addresses the end-of-life management issues to optimize the recycling, reusability and remanufacturing of the disposed products (Jain *et al.*, 2018). However, CE business models in sustainable operations management are perilous and have not figured out the ways of achieving CE. It becomes a challenge to implement and optimize the CE methods in the manufacturing industry. It has been argued that there are conspicuous barriers in adopting CE within the supply chain networks. Furthermore, shortage of reverse treatment technologies, cleaner production systems and lack of information on the product life cycle disrupt the CE principles. Addressing such complexities and exchanging relevant information with subsequent supply chain partners play a critical role in devising a digital supply chain (Ghadimi *et al.*, 2019). Progressive and disruptive manufacturing technologies are able to explore the resources within the closed loop supply chain. Nevertheless, the fourth Industrial revolution – Industry 4.0 – implementation helps in achieving sustainability and fosters the environmental, economic and social dimensions. It has been argued that in respect of sustainability there is no connecting thread between the CE and Industry 4.0. It is a backdrop that manufacturing industries are not able to achieve integrated Industry 4.0-CE, which can significantly increase the efficiency as well as optimize the entire value chain (Ardito *et al.*, 2018). Due to the emergence of Industry 4.0, it may now be possible to overcome technological barriers and achieve CE. Industry 4.0 has the potential to achieve stable patterns of production and consumption so that the production efficiency can be managed through technological innovations. However, there have been many problems in adopting CE within the industries. It has been determined that a lack of information, raw materials movement, shortage of cleaner technologies and timeline for implementation have diminished the CE principles. Nevertheless, as disruptive technologies based on the pillars of Industry 4.0 have emerged, it may now be possible to achieve CE by adopting advanced technologies related to smart manufacturing.

The paper is focused on identifying the Industry 4.0 challenging factors to underpin the CE capabilities and addressing these challenging factors as a basis of the sustainable closed loop supply chain. These Industry 4.0 challenging factors pave the way for the CE principles, which could aid in tracking the raw materials, generating real-time information on production, components, machines and post-consumption of the products. This information can be encapsulated in order to make informed decisions, monitor the performance and trace the life cycle of the product. However, due to the recent emergence of

Industry 4.0, the contextual relationship and the integration of the two important fields, i.e. Industry 4.0 and CE, are partially explored in the existing literature. Based on this, the objective of the study is to identify the Industry 4.0 challenges to implement CE and to stimulate the transformation in CE, thus, preventing the loss of sustainable operations. The CE partially lacks in sustainability, eco-innovation and eco-design, which is creating hurdles in adopting integrated Industry 4.0-CE. Once, the Industry 4.0 challenges are known, the manufacturing industries can achieve CE principles and can unlock the potentials of sustainable manufacturing.

The remaining paper is structured as follows: Section 2 describes the research methodology and review of the past literature on CE and Industry 4.0 barriers, Section 3 provides a brief description of Industry 4.0 barriers, Section 4 presents the hierarchical modeling of Industry 4.0 barriers, Section 5 illustrates the discussion, Section 6 describes managerial implications and theoretical contributions and Section 7 presents the conclusion, limitations and future research directions.

2. Literature review

2.1 Research methodology

The study is performed to evaluate the contemporary literature to explore the potential research gaps and accentuate the knowledge gap. The structured literature review helps in carrying out the analysis, searching the relevant literature through the iterative cycle of defining the appropriate search keywords (Saunders *et al.*, 2009). To maintain the objectivity of the study, the search approach is formulated by first determining the publications from the relevant source that are applicable to Industry 4.0 in CE. The authors have identified various scientific databases like EBSCO, science direct, Scopus and Google Scholar. However, on analyzing deeply, it is determined that Scopus itself contains all publications, which are readily available in other databases as well. For a literature search, Scopus has been used and recommended as the most comprehensive and trusted database (Chicksand *et al.*, 2012).

The literature screening has been performed during the search by reading the abstracts, findings of the study and eliminating the articles where CE and Industry 4.0 have not been the thematic area. For literature search, only those articles are included where authors have claimed that the study contributes to the CE, closed loop material flow, closed supply chain, sustainability, issues of CE and parameters of CE, i.e., economic, environmental and social dimensions. In perspective of Industry 4.0, only those research articles are included, which have contributed to technological advancements, technical development and integration of disruptive technologies in the manufacturing industry. In combined research of CE and Industry 4.0, the search resulted in retrieval of those papers in which authors have determined the technological aspects of Industry 4.0 and CE, the role of Industry 4.0 in CE, designing CE with the aid of technologies, etc. The following sub-sections describe the literature search criteria to include the relevant research papers for the study.

2.1.1 Keywords selection. The authors aimed to cite only those relevant research publications which are associated with the paper title. To collect the relevant articles, the authors mentioned keywords such as Industry 4.0, Circular Economy, Circular Economy and Industry 4.0. But, to analyze the aspects of Industry 4.0 in CE, different keywords were used such as closed-loop supply chain, sustainability, closed economy, smart manufacturing, smart factory, etc. After retrieving the articles, as a preliminary filter, the keywords and abstracts were used and those articles which were not relevant for the study were excluded. During the time of the preliminary search, it was noticed that many research articles contained Industry 4.0 throughout the paper without discussing in the perspectives of CE.

2.1.2 Inclusion criteria. To conduct this study, the peer-reviewed journal was considered as the trusted source of knowledge. The book chapters, books, doctoral thesis, blogs, editorial notes, white papers, etc., were excluded from the study. To keep the relevant publications and meaningful work for the study, exclusion criteria were followed related to Industry 4.0 in the context of CE.

2.1.3 Exclusion criteria. The research publications were collected according to the inclusion criteria and excluded those publications, which were beyond the scope of the work. The introduction, abstract, findings and discussion sections were reviewed, and the articles, which do not focus on applications of Industry 4.0 in CE, were discarded. Those articles were also discarded that did not present the real applications of Industry 4.0, but contained the phrase without analyzing its applicability in CE.

Following the criteria of the literature search, Figures 1–3 depict the growth in the number of publications in the field of Industry 4.0, Figures 4–6 depict the growing trend of CE and Figures 7–9 illustrate the study of CE in the perspectives of Industry 4.0 over the past few years. These figures represent the relevance of Industry 4.0 and CE for the study where two emerging fields are partially explored and considered as the need of an hour.

2.2 Review on circular economy and Industry 4.0 barriers

The limitation of the linear economy model is incompetency in balancing the supply and demand of natural resources. Due to this, the planet’s sustainability and socio-economic conditions are deteriorating. In the light of limitations and challenges of linear economy

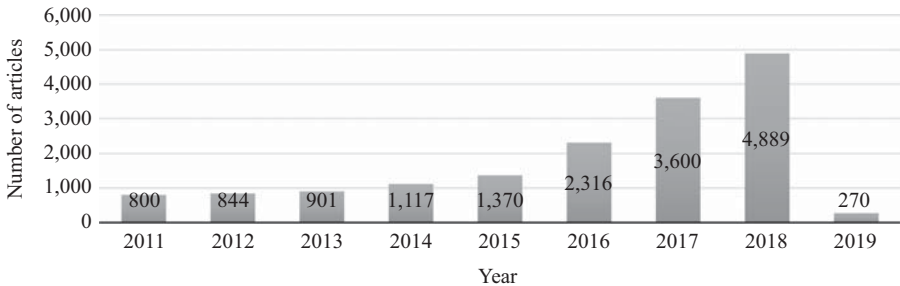


Figure 1. Industry 4.0 under “text” only

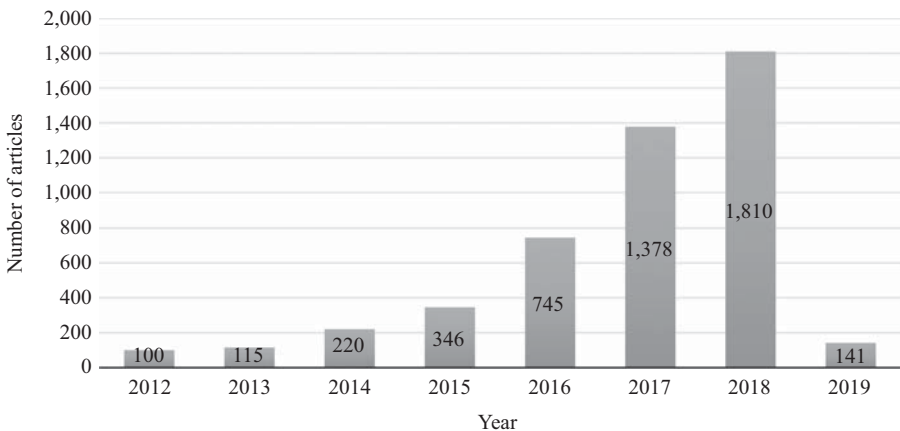


Figure 2. Industry 4.0 under “title, abstract or keywords”

Challenges to implement CE

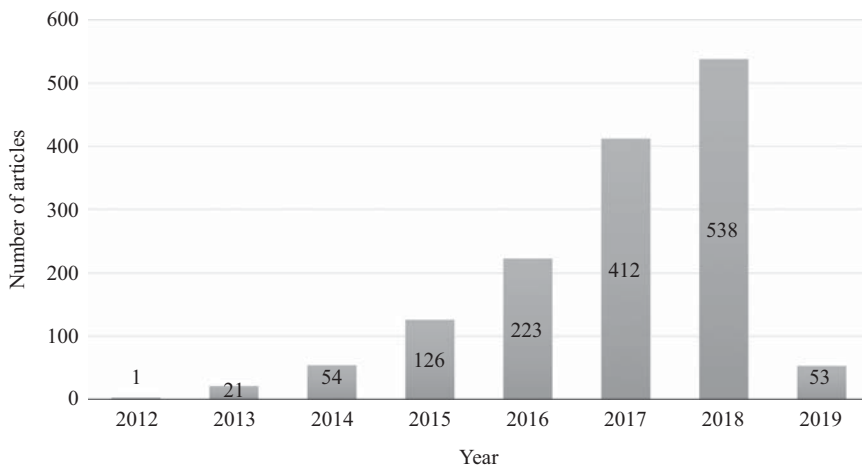


Figure 3.
Industry 4.0 under
“title” only

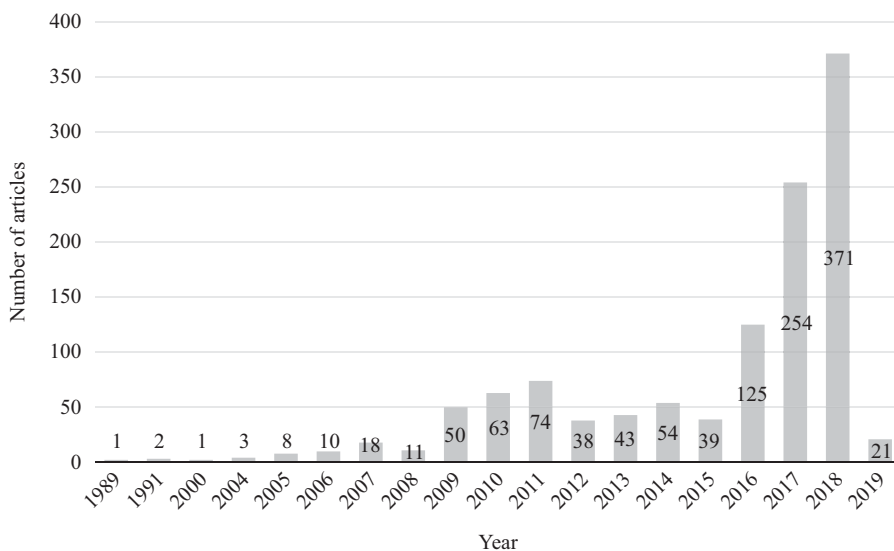


Figure 4.
Circular economy
under “title” only

approach, i.e., take–make–dispose, the CE is considered as an optimal solution for the global economy. The concept of CE came into the picture in the 1970s which describes how the natural resources maintain the production and consumption patterns as well as provides concavity for wastes in the form of outputs (Andersen, 2007). Later, it was revived in China in the 1990s in the context of economic development and natural resource constraints (Geng and Doberstein, 2008). Previous studies on CE provide prospective understanding and applications of CE in redesigning the manufacturing systems and share the ideas of the closed loop supply chain (Geissdoerfer *et al.*, 2017). It is argued that to meet the potential needs of the global economy, CE does not address the economic, business and social aspects. It is still unclear, how CE will meet these aspects and will justify the three pillars of sustainability namely, economic, environment and social. These three important pillars have no connecting thread in the sustainable supply chain network and require rigorous

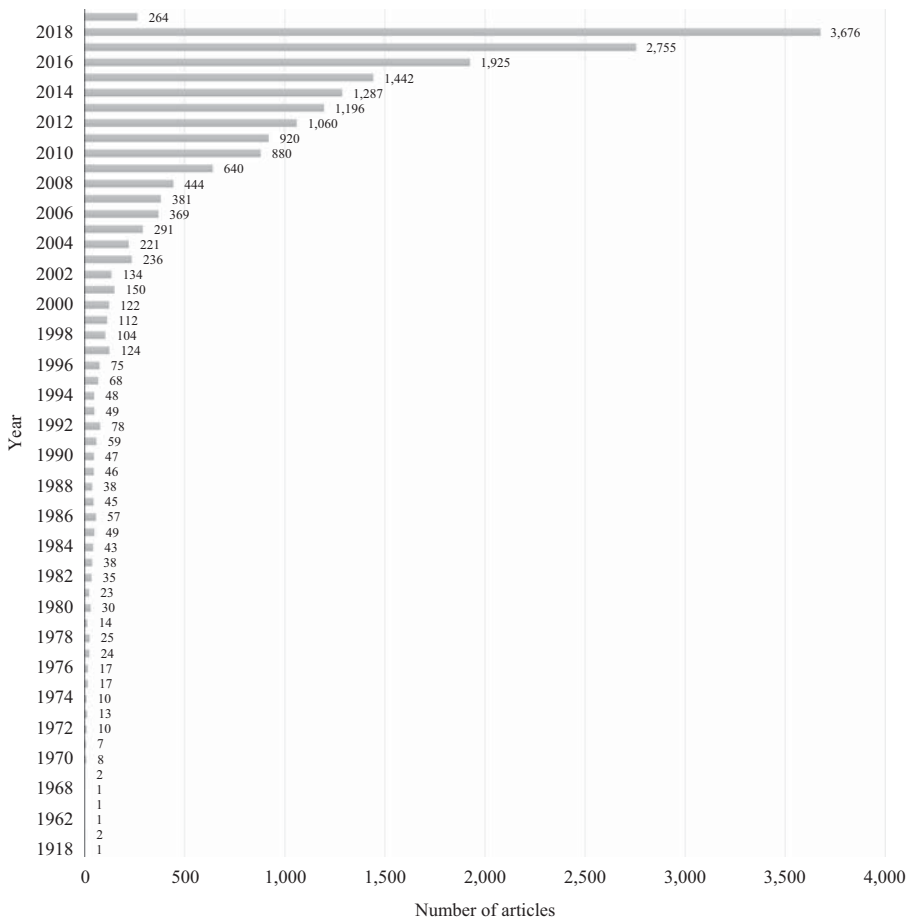


Figure 5. Circular economy under “text” only

attention (Gray *et al.*, 1995; Chauhan *et al.*, 2019). The main purpose of the CE is to gain a hold on materials recycling and to balance economic and environmental growth (Winans *et al.*, 2017).

To transform linear economy to CE, advancing technologies building the path toward sustainability, considering the technological inclination of Industry 4.0. However, a technological gap exists related to how the manufacturing industries should move toward sustainable operations and achieve CE principles (Stock and Seliger, 2016). CE approach generates a huge amount of data with respect to wastage, byproduct, raw material, etc., and requires digitization in the supply chain to monitor and access the real-time information. In this direction, Industry 4.0 provides key innovation in sustainable operations and makes the chain more dynamic and efficient. To this effect, many authors have contributed their studies to evaluating and determining the success factors, enablers, features and requirements of Industry 4.0 for effective implementation. Arora *et al.* (2006), Miorandi *et al.* (2012), Athreya and Tague (2013), Monostori (2014), Pozza *et al.* (2015), Zhong *et al.* (2016), Ahmed *et al.* (2017) and Rajput and Singh (2018) determined essential enablers, namely, flexibility, reliability, scalability, self-adaptation, big data, predictive maintenance, service recovery, quality of service, self-optimization, integration, interoperability, interfacing and

Challenges to implement CE

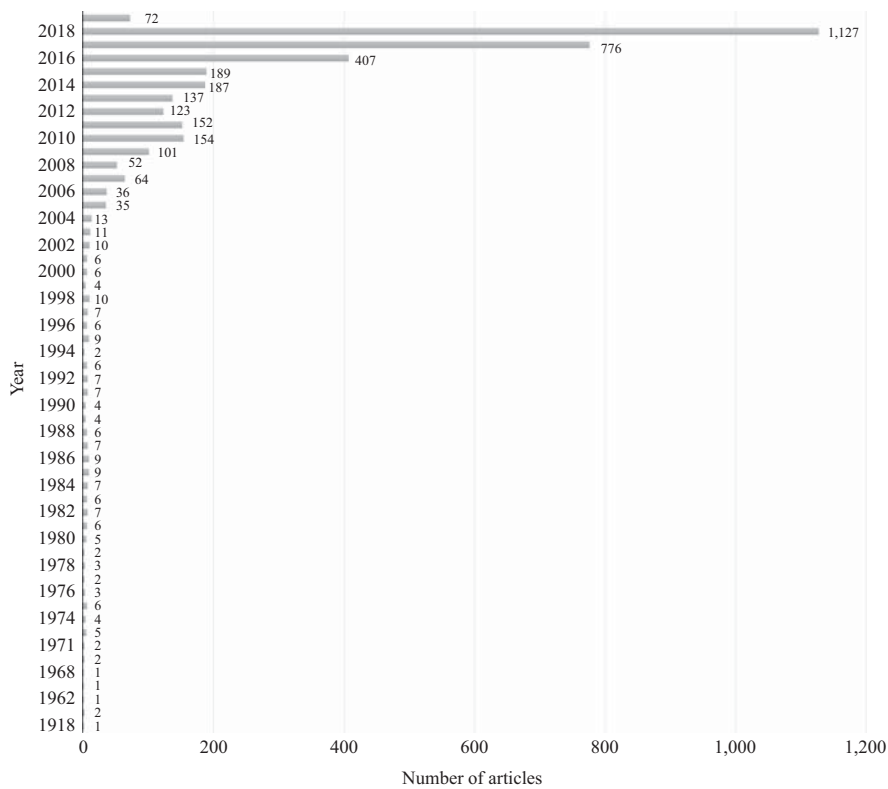


Figure 6. Circular economy under “title, abstract or keywords”



Figure 7. Industry 4.0 and circular economy under “title” only

networking capabilities, etc., but current research studies lack in identifying the barriers, which hinder the manufacturing industries to implement Industry 4.0 to maintain sustainability in a closed-loop supply chain.

For the purpose of this study, Industry 4.0 involves challenges, difficulties which are identified, as it is not easy to achieve all the enablers. The limited study is done in identifying the Industry 4.0 barriers. The limited study is done in identifying the Industry 4.0 barriers such as CPS modeling and integration, data analysis, CPS standards and specifications, investment cost, collaborative model and smart devices development (Zhou *et al.*, 2015). CPS has spatio-temporal properties, and it requires accurate and real-time decision-making information by the event handler in order to ensure accurate physical system control in time and space. Therefore, collaboration between the real and physical

Figure 8.
Industry 4.0 and circular economy under “text” only

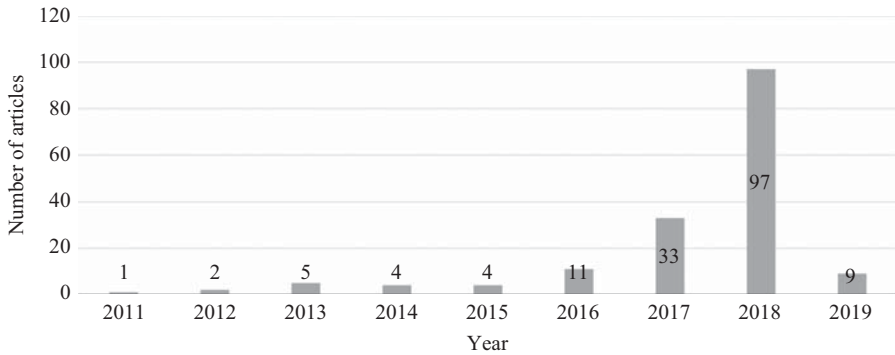
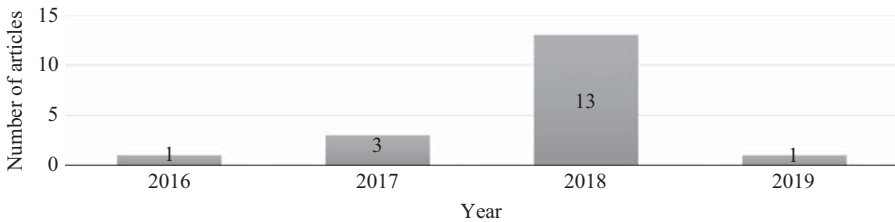


Figure 9.
Industry 4.0 and circular economy under “title, abstract or keywords”



world needs to be considered. CPS calculation process requires discrete logical time, and the physical process requires continuous physical time. Therefore, it is difficult to use different computing models to build CPS modeling with a consolidated framework. Apart from this, CPS works with heterogeneous devices/components and deals with voluminous data, which makes its behavior more complex. Additionally, new CPS modeling language is required to fit in the complex environment. Therefore, uniform standards and specifications of the CPS are required. Industry 4.0 factory works intelligently and smartly with artificial and smart/IoT devices, which minimize human involvement. However, different factories require different smart device development and configurations, which require investment cost and time before it is implemented in any of the smart factories.

Other challenges related to infrastructure are standardization, compatibility and design (Leitao *et al.*, 2016). Standardizing or designing the infrastructure to handle computationally intensive tasks and to develop self-adaptation becomes complex. Sensor technology development for Industry 4.0 is required to detect errors and failures and to communicate smartly with smart devices. Similarly, smart services aid in improving time, reducing cost and developing consumer–manufacturers interconnection. Therefore, implementing disruptive technologies and its training is one of the most difficult barriers for a smart factory (<https://clr.es/blog/en/main-challenges-of-industry-4-0/>). Fog computation improves IoT solution and is a geographically distributed system connected with multiple devices at the edge of the network. On the contrary, several issues that are mentioned in research studies and are not considered for solving or decreasing the complexity of these challenges such as security, interfacing and network, interoperability, latency, heterogeneity, security, resource management, etc. Fog computing is considered as a solution for IoT applications, but it has limited capabilities such as networking, computing and storing. Industry 4.0 enhances mobility with the support of IoT as well as privacy and security, but it is a challenge in the fog computing environment (Atlam *et al.*, 2018). Luthra and Mangla (2018) pointed out Industry 4.0 challenges, namely, global standards and data sharing protocols,

security and unclear benefit in digital investment. Zhu *et al.* (2010) mentioned that eco-efficiency, take-back ratio and eco-design are the critical factors to achieve CE principles. Other barriers such as automation system virtualization, process digitalization and product technology improvement can be referred from the work of Usman *et al.* (2014), Elkhodr *et al.* (2016) and Govindan and Hasanagic (2018). The detailed work of Industry 4.0 barriers can be referred from Rajput and Singh (2019). The brief description of these barriers is discussed in Section 3.

3. Barriers identification

Based on experts' opinion and extensive literature review, 20 barriers were identified. A brief description of these barriers is provided in this section. However, the detailed description can be referred from the respective papers cited in the literature review section:

- (1) Sensor technology: Industry 4.0 operations require sensors technology such as RFID to capture the voluminous information and form a network with other component/devices.
- (2) Process digitization: Industry 4.0 induces mobility in the processes and reduces the cost, computerizes the production processes and implements new advanced and disruptive technologies.
- (3) Data analysis: voluminous data are captured in different formats; therefore, analytics is required to analyze data and to retrieve information as per user-readiness.
- (4) Fog computing: it provides data storage and processing services locally to fog devices rather than storing on the cloud.
- (5) Infrastructure standardization: infrastructure is required to equip the advanced technologies. It is required to integrate the heterogeneous devices/components in automation systems.
- (6) Semantic interoperability: to execute the transaction of data between the two or more machines, a protocol is required for different devices for efficient and effective communication.
- (7) Smart devices development: different advanced and smart devices are required to communicate in Industry 4.0 environment to reduce the human intervention.
- (8) CPS modeling and modeling integration: CPS model interacts between the physical and virtual world and also involves the physical and computing components. Therefore, CPS requires different computing models with a unified framework.
- (9) CPS standards and specifications: it is required for the validation to ensure that the system is capable to handle the specific requirements.
- (10) Automation system virtualization: it maximizes the real-time visibility of the operation processes, which offers reliable and efficient solutions.
- (11) Collaboration and coordination: it is required for direct interaction with the humans and also designed robots offers safety work to the humans within a defined workspace.
- (12) Design challenges: it is required to design the business model and to include the CPS-enabled landscapes.
- (13) Interfacing and network: it enables underlying wireless technologies and sensor technology to interface with the physical world.
- (14) Compatibility: it keeps the system's components working together in a functioning environment without implementing any changes to the system.

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- (15) Investment cost: it is required to standardize the infrastructure, develop smart devices and sensor technology.
 - (16) Smart services: data of physical devices are acquired as digital services to create value and intangible benefits for the users.
 - (17) Product technology improvement: it is required to manage the product quality throughout the life cycle of the product as well as to maintain durability, reliability, etc.
 - (18) Eco-efficiency of technological processes: integrating the sustainability in the process increases the whole eco-system's efficiency and effectiveness.
 - (19) Global standards and data sharing protocols: industry 4.0 requires intelligence mechanisms to process the data; therefore, prerequisites standards and protocols are essential for data sharing.
 - (20) Security: industry 4.0 maintains the network across the value chain; therefore, security vulnerability is high in attacking the system.

4. Hierarchical modeling for Industry 4.0 barriers for CE

Warfield (1974) developed the interpretive structural modeling (ISM) methodology. It is an interactive learning process in which a set of pertinent elements is portrayed in a hierarchical model. It is used for determining the relationships between the various elements relevant to the study. It transforms poor, unclear articulated models into visible, defined hierarchical model used for many applications by determining their complex relationship (Mandal and Deshmukh, 1994). The ISM methodology can be referred from the work of Raut *et al.* (2018), Goyal and Kumar (2017) and Digalwar *et al.* (2017).

The following steps are for the development of the hierarchical model for Industry 4.0 barriers.

4.1 Identification of Industry 4.0 barriers for CE

For the study, the data are collected from experts of the manufacturing sector and academicians working in the area of Industry 4.0 implementation. The mode of data collection is an online survey. In all, 20 Industry 4.0 barriers for the implementation of CE have been identified through experts' opinion and extensive literature study. These are, namely, (B1) smart services, (B2) automation system virtualization, (B3) compatibility, (B4) interfacing and network, (B5) semantic interoperability, (B6) sensor technology, (B7) process digitalization, (B8) product technology improvement, (B9) data analysis, (B10) design challenges, (B11) CPS modeling and integration, (B12) collaboration and coordination, (B13) CPS standards and specifications, (B14) fog computing, (B15) eco-efficiency of technological processes, (B16) global standards and data sharing protocols, (B17) security, (B18) investment cost, (B19) smart devices development and (B20) infrastructure standardization.

4.2 SSIM

The SSIM depicts the pair-wise relationships between each pair of barriers. For analysis, the barrier "leads to" or influences are chosen for a contextual relationship. This means that one barrier leads to or influences another barrier. Based on the rules of V, A, X and O, SSIM is constructed.

4.3 Reachability matrix from SSIM

An initial reachability matrix (Table I) is constructed from the SSIM. Considering the transitivity rules, a final reachability matrix (Table II) is obtained.

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	Challenges to implement CE
B1	1	0	0	0	0	0	0	1	1	0	
B2	1	1	0	0	0	0	0	1	1	0	
B3	1	1	1	1	1	1	0	1	0	0	
B4	0	0	0	1	1	1	0	1	0	0	
B5	1	1	0	0	1	1	0	1	0	1	
B6	1	1	0	0	0	1	0	1	1	1	
B7	1	0	1	1	1	1	1	1	0	1	
B8	0	0	0	0	0	0	0	1	0	0	
B9	0	0	0	0	0	0	0	1	1	0	
B10	1	1	0	0	0	0	0	1	0	1	
B11	0	0	0	0	0	0	0	0	1	0	
B12	1	1	0	0	0	0	0	1	1	0	
B13	1	1	0	0	0	0	0	1	0	1	
B14	0	0	1	1	0	0	1	1	1	1	
B15	0	0	0	0	0	0	0	0	0	0	
B16	1	1	1	1	0	0	0	0	0	0	
B17	1	1	1	1	0	0	0	0	0	0	
B18	1	1	1	1	0	0	0	0	0	0	
B19	1	1	1	1	0	0	0	0	0	0	
B20	1	1	1	1	1	1	0	0	0	0	
Barriers	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20	
B1	0	0	0	0	1	1	1	1	1	0	
B2	1	0	0	0	1	1	1	1	1	0	
B3	1	0	0	1	1	1	1	1	1	0	
B4	1	0	0	1	1	1	1	1	1	0	
B5	1	0	0	0	0	0	0	1	1	0	
B6	1	0	1	0	0	0	0	1	1	0	
B7	1	1	1	0	0	0	0	0	0	0	
B8	1	0	0	0	0	0	0	0	0	0	
B9	0	0	0	0	0	0	0	0	0	0	
B10	1	0	0	0	0	0	0	0	0	0	
B11	1	0	0	1	1	1	1	0	0	0	
B12	1	1	0	0	1	1	1	0	0	0	
B13	1	1	1	0	1	1	1	0	0	0	
B14	1	0	0	1	1	1	1	1	1	0	
B15	0	0	0	1	1	1	1	1	1	0	
B16	0	0	0	1	1	1	1	1	1	0	
B17	0	0	0	1	1	1	1	1	1	0	
B18	0	1	0	0	1	1	1	1	1	0	
B19	0	1	0	0	1	1	1	1	1	0	
B20	0	0	1	0	0	0	0	1	1	1	

Table I.
Initial reachability matrix

4.4 Partitioning the reachability matrix

By segregating the reachability matrix, the reachability set and antecedent set of each barrier are formed through successive iterations. In Table III, barriers, namely, product technology improvement (B8), CPS modeling and integration (B11) and eco-efficiency of technological process (B15) are positioned at the highest level in the ISM hierarchy. With subsequent iterations, the level of each barriers is obtained. Table IV provides the complete levelling of each barriers. The iterations for each barrier are shown in Tables AI–AIX.

4.5 Developing interpretive structural modeling model

From the final reachability matrix (Table II), the hierarchical model is obtained, depicted in the following Figure 10. The hierarchical level of the barriers is illustrated in Table IV.

Table II.
Final reachability matrix

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20	Driving Power	
B1	1	1*	1*	1*	0	0	1*	1	1	0	1*	1*	0	1*	1	1	1	1	1	0	15	
B2	1	1	1*	1*	0	0	0	1	1	0	1	1*	0	1*	1	1	1	1	1	0	14	
B3	1	1	1	1	1	1	1*	1	1*	1*	1	1*	1*	1	1	1	1	1	1	0	19	
B4	1*	1*	1*	1	1	1	1*	1	1*	1*	1	1*	1*	1	1	1	1	1	1	0	19	
B5	1	1	1*	1*	1	1	0	1	1*	1	1	1*	1*	1*	1*	1*	1*	1	1	0	18	
B6	1	1	1*	1*	0	1	0	1	1	1	1	1*	1	1*	1*	1*	1*	1	1	0	17	
B7	1	1*	1	1	1	1	1	1	1*	1	1	1	1	1*	1*	1*	1*	1*	1*	1*	20	
B8	0	0	0	0	0	0	0	1	0	0	1	0	0	1*	1*	1*	1*	0	0	0	6	
B9	0	0	0	0	0	0	0	1	1	0	1*	0	0	0	0	0	0	0	0	0	3	
B10	1	1	0	0	0	0	0	1	1*	1	1	0	0	1*	1*	1*	1*	1*	1*	0	12	
B11	1*	1*	1*	1*	0	0	1*	1*	1	0	1	0	0	1	1	1	1	1	1*	1*	0	14
B12	1	1	1*	1*	0	0	0	1	1	0	1	1	0	1*	1	1	1	1*	1*	0	14	
B13	1	1	1*	1*	0	0	0	1	1*	1	1	1	1	1*	1	1	1	1*	1*	0	16	
B14	1*	1*	1	1	1*	1*	1	1	1	1	1	1*	1*	1	1	1	1	1	1	0	19	
B15	1*	1*	1*	1*	0	0	1*	1*	1*	1*	1*	1*	0	1	1	1	1	1	1	0	16	
B16	1	1	1	1	1*	1*	1*	1*	1*	1*	1*	1*	0	1	1	1	1	1	1	0	18	
B17	1	1	1	1	1*	1*	1*	1*	1*	1*	1*	1*	0	1	1	1	1	1	1	0	18	
B18	1	1	1	1	1*	1*	0	1*	1*	0	1*	1	0	1*	1	1	1	1	1	0	16	
B19	1	1	1	1	1*	1*	0	1*	1*	0	1*	1	0	1*	1	1	1	1	1	0	16	
B20	1	1	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0	1	1	1	10	
Dependence	18	18	17	17	10	11	9	19	18	11	19	15	8	18	18	18	18	18	18	2		

Note: *Signify transitivity link

4.6 Matriced’ impacts croised-multiplication applique’ and classment (MICMAC) analysis

The MICMAC (cross-matrix multiplication applied to classification) is basically used to differentiate the enablers into four categories, i.e., autonomous, dependent, linkage and independent according to their driving power and dependence as shown in Figure 11.

Based on the categorization, the barriers are grouped as follows:

- Autonomous barrier is B20 and is relatively isolated from the system and has weak dependence as well as weak driving power.
- Dependent barriers are B8 and B9 and have weak driving power and strong dependence.
- Linkage barriers are B1, B2, B3, B4, B11, B12, B14, B15, B16, B17, B18 and B19 and any effect on these barriers will probably affect other barriers as well. These barriers have high dependence as well as high driving power.
- Independent barriers are B5, B6, B7, B10 and B13 and have strong driving power and weak dependence.

5. Discussion

The paper illustrates the structural model (Figure 10) and MICMAC diagram (Figure 11). It distinguishes various Industry 4.0 barriers with respect to their driving power and dependence. On analyzing MICMAC, it is illustrated that one barrier is classified as autonomous variables, which means that one barrier is aloof from the system and should consider all other Industry 4.0 barriers for achieving CE. The barriers categorized in the second group, i.e., dependent variables have high dependence and weak driving power. The barriers in this group are (B8) product technology improvement and (B9) data analysis. These barriers are crucial for achieving a CE, and due to their high dependence, they need other barriers to drive them. The other cluster in the MICMAC analysis is linkage and barriers in this cluster namely, (B1) smart services, (B2) automation system virtualization (B3) compatibility, (B4) interfacing and networking, (B11) CPS modeling and integration, (B12) collaboration and coordination, (B14) fog computation, (B15) eco-efficiency of technological processes, (B16) global standards and data sharing protocols, (B17) security, (B18) investment cost and (B19) smart devices development. These barriers are highly dependent and highly driving. Therefore, any effect on one barrier will also influence other

Barriers	Reachability set	Antecedent set	Intersection set	Level
B1	1, 2, 3, 4, 7, 8, 9, 11, 12, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	1, 2, 3, 4, 7, 11, 12, 14, 15, 16, 17, 18, 19	I
B2	1, 2, 3, 4, 8, 9, 11, 12, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	1, 2, 3, 4, 11, 12, 14, 15, 16, 17, 18, 19	I
B3	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	1, 2, 3, 4, 5, 6, 7, 11, 12, 13, 14, 15, 16, 17, 18, 19	I
B4	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	1, 2, 3, 4, 5, 6, 7, 11, 12, 13, 14, 15, 16, 17, 18, 19	I
B5	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	3, 4, 5, 7, 14, 16, 17, 18, 19, 20	3, 4, 5, 14, 16, 17, 18, 19	I
B6	1, 2, 3, 4, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	3, 4, 5, 6, 7, 14, 16, 17, 18, 19, 20	3, 4, 6, 14, 17, 18, 19	I
B7	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	1, 3, 4, 7, 11, 14, 15, 16, 17	1, 3, 4, 7, 11, 14, 15, 16, 17	I
B8	8, 11, 14, 15, 16, 17	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	8, 11, 14, 15, 16, 17	I
B9	8, 9, 11	1, 3, 4, 7, 11, 14, 15, 16, 17	9, 11	I
B10	1, 2, 8, 9, 10, 11, 14, 15, 16, 17, 18, 19	3, 4, 5, 6, 7, 10, 13, 14, 15, 16, 17	10, 14, 15, 16, 17	I
B11	1, 2, 3, 4, 7, 8, 9, 11, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 7, 8, 9, 11, 14, 15, 16, 17, 18, 19	I
B12	1, 2, 3, 4, 8, 9, 11, 12, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 12, 14, 15, 16, 17, 18, 19	I
B13	1, 2, 3, 4, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	3, 4, 5, 6, 7, 13, 14, 20	3, 4, 13, 14	I
B14	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	I
B15	1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18, 19	I
B16	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 14, 15, 16, 17, 18, 19	I
B17	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 14, 15, 16, 17, 18, 19	I
B18	1, 2, 3, 4, 5, 6, 8, 9, 11, 12, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	2, 3, 4, 5, 6, 11, 12, 14, 15, 16, 17, 18, 19	I
B19	1, 2, 3, 4, 5, 6, 8, 9, 11, 12, 14, 15, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	1, 2, 3, 4, 5, 6, 11, 12, 14, 15, 16, 17, 18, 19	I
B20	1, 2, 3, 4, 5, 6, 13, 18, 19, 20	7, 20	20	I

Challenges to
implement CE

Table III.
Iteration 1

Table IV.
Levels of Industry
4.0 barriers

Barriers	Reachability set	Antecedent set	Intersection set	Level
B9	9	1,2,3,4,5,6,7,9,10,12,13,14,16,17,18,19	9	II
B1	1,2,3,4,7,12,14,16,17,18,19	1,2,3,4,5,6,7,10,12,13,14,16,17,18,19,20	1,2,3,4,7,12,14,16,17,18,19	III
B2	1,2,3,4,12,14,16,17,18,19	1,2,3,4,5,6,7,10,12,13,14,16,17,18,19,20	1,2,3,4,12,14,16,17,18,19	III
B12	1,2,3,4,12,14,16,17,18,19	1,2,3,4,5,6,7,12,13,14,16,17,18,19	1,2,3,4,12,14,16,17,18,19	III
B14	1,2,3,4,5,6,7,10,12,13,14,16,17,18,19	1,2,3,4,5,6,7,10,12,13,14,16,17,18,19	1,2,3,4,5,6,7,10,12,13,14,16,17,18,19	III
B16	1,2,3,4,5,6,7,10,12,14,16,17,18,19	1,2,3,4,5,6,7,10,12,13,14,16,17,18,19	1,2,3,4,5,6,7,10,12,14,16,17,18,19	III
B17	1,2,3,4,5,6,7,10,12,14,16,17,18,19	1,2,3,4,5,6,7,10,12,13,14,16,17,18,19	1,2,3,4,5,6,7,10,12,14,16,17,18,19	III
B19	1,2,3,4,5,6,12,14,16,17,18,19	1,2,3,4,5,6,7,10,12,13,14,16,17,18,19,20	1,2,3,4,5,6,12,14,16,17,18,19	III
B18	3,4,5,6,18	3,4,5,6,7,10,13,18,20	3,4,5,6,18	IV
B10	10	3,4,5,6,7,10,13	10	V
B3	3,4,5,6,7,13	3,4,5,6,7,13,20	3,4,5,6,7,13	VI
B4	3,4,5,6,7,13	3,4,5,6,7,13,20	3,4,5,6,7,13	VI
B13	3,4,13	3,4,5,6,7,13,20	3,4,13	VI
B6	6	5,6,7,20	6	VII
B5	5	5,7,20	5	VIII
B20	20	7,20	20	IX
B7	7	7	7	X

Challenges to implement CE

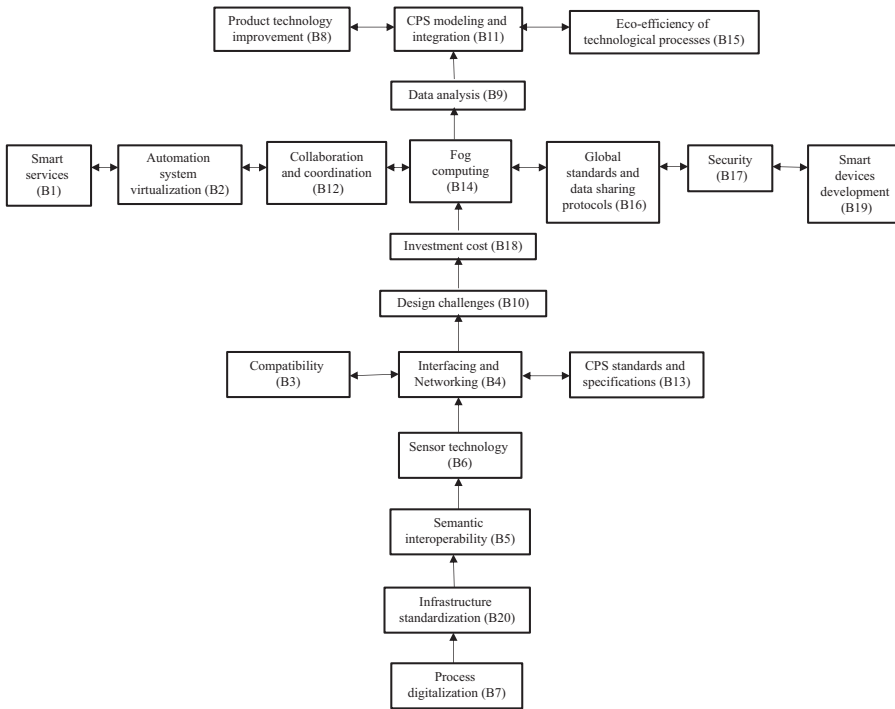


Figure 10.
ISM model of Industry 4.0 barriers

Driving power	20	Independent	B7 B5		B3, B4, B14 Linkage	B19, B18 B15 B2, B11
	16		B13	B6	B12	B1
	12			B10		
	8		Autonomous		Dependent	B8
	4					B9
		4	8	12	16	20
Dependence						

Figure 11.
MICMAC analysis of Industry 4.0 barriers

barriers in the system. The fourth group is independent barriers, namely, (B5) semantic interoperability, (B6) sensor technology, (B7) process digitalization, (B10) design challenge and (B13) CPS standards and specifications. These barriers have high driving power and low dependence. These barriers play a significant role in improving resource efficiency and sustainability and the absence of these barriers may not drive other barriers for gaining CE.

6. Managerial implications and theoretical contributions

The paper focusses on identifying the Industry 4.0 barriers to achieve CE. Due to the knowledge gap, many studies have not highlighted the transition link between Industry 4.0 and CE. Recent studies have focused on the theoretical contribution of critical success factors and enablers to gain resource efficiency, carbon emission, energy consumption and sustainable production. However, limited studies are available on the issues of Industry 4.0 and mainly reviewed work on the generic challenges of Industry 4.0. The present study provides specific barriers of Industry 4.0 in paving the way for CE. The study investigates the Industry 4.0 barriers for sustainable operations and CE strategies, taking into account the technological benefits of Industry 4.0. This leads to a shared network of manufacturing resources, developing new business models, integrating manufacturing-related technologies as well as controlling processes and components in real time. Implementing integrated Industry 4.0-CE involves probable challenges; therefore, manufacturing industries should focus on these emerging barriers. The study provides an insight for the organization to focus on those barriers, particularly which are hindering the CE, i.e. process digitalization and semantic interoperability. These barriers are having low dependence and high driving power among all the identified barriers as shown in MICMAC analysis (Figure 11). These barriers inhibit the optimization of the sustainability opportunities, which naturally leads to whether Industry 4.0 will provide the optimum solution.

The organizations are facing problems in implementing Industry 4.0 due to the paucity of technological and technical knowledge of CE and Industry 4.0. From the perspective of managerial implications, the main driving barriers as shown in MICMAC diagram (Figure 11), i.e., process digitalization, semantic interoperability, sensor technology, CPS standards and specifications and design challenges are inhibiting the CE. If these Industry 4.0 barriers are considered, then manufacturing industries can uplift their process in terms of eco-design, eco-innovation, remanufacturing, managing the wastes, by-products and supply chain networks. The manufacturing industries can gain promising solutions from integrated Industry 4.0-CE such as monitoring the wastes, natural resources, revamping the closed loop supply chains into technological supply networks and controlling the carbon and energy consumption. Moreover, the industry experts can rebuild their CE business models to balance the environmental and economic behavior for the implementation of the eco-design principles. The industry experts can also focus on the barriers, which are categorized as linkage barriers, as any activity on one barrier can influence the other barriers in the system. Additionally, integrated Industry 4.0-CE gives an opportunity for customization where Industry 4.0 facilitates the communication between the customers and products to provide extreme services to the end customers. Even industry experts could monitor the performance of the operations through sensors as well as the efficiency of the machines could also be assessed in real time for predictive maintenance and service recovery.

The essence of the study is that the different Industry 4.0 barriers are explored and analyzed for maintaining CE. The findings of the study confirm that integrated Industry 4.0-CE has the potential for enhancing the triple bottom line of sustainability by optimizing the raw materials, scrapped products and carbon footprint. It provides prodigious opportunities for production and logistics decisions based on the data provided by the resources of IoT. This leads to the revenue generation opportunity for the manufacturing industry to maximize the value creation of products with the compelling recovery of resources from different varieties of post-usage products, by-products and production wastages. The driving prominent barriers compel in automating the circular supply chain, semantic communication between the machines and products, capturing information throughout the system and improve the production and consumption rate to enhance sustainable operations. As a consequence, the manufacturing industries are involved in end-to-end integration focusing on the improvement in efficiency and increasing the precision and accuracy of the sustainable supply chain.

7. Conclusion, limitations and future research directions

The manufacturing industries are aligning toward the closed-loop supply chain, and Industry 4.0 has the potential to unlock the opportunities of the CE. The paper aims to identify the Industry 4.0 barriers to enhance the CE approaches and to maintain sustainability because the link between the CE and Industry 4.0 is unserved. The prominent barriers derived from the ISM hierarchical model are process digitalization and semantic interoperability. If industry experts pay keen attention to these barriers, then the problem of sharing technological and manufacturing data across the system would be error free with minimal human intervention. Besides this, the clear emphasis would be on a repository of the post-usage product information, sustainable production and consumption, carbon emission, process automation, materials, etc. Integrated Industry 4.0-CE will aid manufacturing industry experts to track the raw materials and monitor the manufacturing equipment how to get the desired end product. Ultimately, Industry 4.0 serves the purpose of 3R's, i.e., reduce, reuse and recycle to fetch the CE and keeps the product, materials and components usage value for the prolonged period. Therefore, the key barriers hindering in achieving the CE and identification of these barriers could be a major step toward sustainable operations management.

The limitation of the study is that the contextual relationship has been established between the barriers based on the opinion of the area experts' and academicians, which can have a certain degree of biases. For the study, only 20 barriers were considered, more Industry 4.0-related barriers can be identified for future research. Quantitative/qualitative techniques can be applied for prioritizing, deriving cause-effect relationship, optimizing the deliverables of CE and analyzing how Industry 4.0 could help in addressing the issues of sustainable operations. For future perspectives, the detailed study of the barriers and understanding of their underlying technology facilitate effective implementation of Industry 4.0. This motivates the technical development of reusing and remanufacturing products and can be better dedicated to the automation and innovation of the processes.

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Further reading

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Barriers	Reachability set	Antecedent set	Intersection set	Level
B1	1, 2, 3, 4, 7, 9, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19, 20	1, 2, 3, 4, 7, 12, 14, 16, 17, 18, 19	
B2	1, 2, 3, 4, 9, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19, 20	1, 2, 3, 4, 12, 14, 16, 17, 18, 19	
B3	1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 16, 17, 18, 19, 20	1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 16, 17, 18, 19	
B4	1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 16, 17, 18, 19, 20	1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 16, 17, 18, 19	
B5	1, 2, 3, 4, 5, 6, 9, 10, 12, 13, 14, 16, 17, 18, 19	3, 4, 5, 7, 14, 16, 17, 18, 19, 20	3, 4, 5, 14, 16, 17, 18, 19	
B6	1, 2, 3, 4, 6, 9, 10, 12, 13, 14, 16, 17, 18, 19	3, 4, 5, 6, 7, 14, 16, 17, 18, 19, 20	3, 4, 6, 14, 17, 18, 19	
B7	1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 13, 14, 16, 17, 18, 19, 20	1, 3, 4, 7, 14, 16, 17	1, 3, 4, 7, 14, 16, 17	
B9	9	9	9	II
B10	1, 2, 9, 10, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 13, 14, 16, 17, 18, 19	10, 14, 16, 17	
B12	1, 2, 3, 4, 9, 12, 14, 16, 17, 18, 19	3, 4, 5, 6, 7, 10, 13, 14, 16, 17	1, 2, 3, 4, 12, 14, 16, 17, 18, 19	
B13	1, 2, 3, 4, 9, 10, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 16, 17, 18, 19	3, 4, 13, 14	
B14	1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 13, 14, 16, 17, 18, 19	3, 4, 5, 6, 7, 13, 14, 20	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19	
B16	1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 14, 16, 17, 18, 19	
B17	1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 14, 16, 17, 18, 19	
B18	1, 2, 3, 4, 5, 6, 9, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 20	2, 3, 4, 5, 6, 12, 14, 16, 17, 18, 19	
B19	1, 2, 3, 4, 5, 6, 9, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19, 20	1, 2, 3, 4, 5, 6, 12, 14, 16, 17, 18, 19	
B20	1, 2, 3, 4, 5, 6, 13, 18, 19, 20	7, 20	20	

Table AI.
Iteration 2

Barriers	Reachability set	Antecedent set	Intersection set	Level
B1	1, 2, 3, 4, 7, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19, 20	1, 2, 3, 4, 7, 12, 14, 16, 17, 18, 19	III
B2	1, 2, 3, 4, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19, 20	1, 2, 3, 4, 12, 14, 16, 17, 18, 19	III
B3	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 16, 17, 18, 19, 20	1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 16, 17, 18, 19	
B4	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 16, 17, 18, 19, 20	1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 16, 17, 18, 19	
B5	1, 2, 3, 4, 5, 6, 10, 12, 13, 14, 16, 17, 18, 19	3, 4, 5, 7, 14, 16, 17, 18, 19, 20	3, 4, 5, 14, 16, 17, 18, 19	
B6	1, 2, 3, 4, 6, 10, 12, 13, 14, 16, 17, 18, 19	3, 4, 5, 6, 7, 14, 16, 17, 18, 19, 20	3, 4, 6, 14, 17, 18, 19	
B7	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19, 20	1, 3, 4, 7, 14, 16, 17	1, 3, 4, 7, 14, 16, 17	
B10	1, 2, 10, 14, 16, 17, 18, 19	3, 4, 5, 6, 7, 10, 13, 14, 16, 17	10, 14, 16, 17	
B12	1, 2, 3, 4, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 12, 14, 16, 17, 18, 19	III
B13	1, 2, 3, 4, 10, 12, 13, 14, 16, 17, 18, 19	3, 4, 5, 6, 7, 13, 14, 20	3, 4, 13, 14	
B14	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19	III
B16	1, 2, 3, 4, 5, 6, 7, 10, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 14, 16, 17, 18, 19	III
B17	1, 2, 3, 4, 5, 6, 7, 10, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 14, 16, 17, 18, 19	III
B18	1, 2, 3, 4, 5, 6, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19, 20	2, 3, 4, 5, 6, 12, 14, 16, 17, 18, 19	III
B19	1, 2, 3, 4, 5, 6, 12, 14, 16, 17, 18, 19	1, 2, 3, 4, 5, 6, 7, 10, 12, 13, 14, 16, 17, 18, 19, 20	1, 2, 3, 4, 5, 6, 12, 14, 16, 17, 18, 19	III
B20	1, 2, 3, 4, 5, 6, 13, 18, 19, 20	7, 20	20	III

BJ

Barriers	Reachability set	Antecedent set	Intersection set	Level
B3	3, 4, 5, 6, 7, 10, 13, 18	3, 4, 5, 6, 7, 13, 18, 20	3, 4, 5, 6, 7, 13, 18	
B4	3, 4, 5, 6, 7, 10, 13, 18	3, 4, 5, 6, 7, 13, 18, 20	3, 4, 5, 6, 7, 13, 18	
B5	3, 4, 5, 6, 10, 13, 18	3, 4, 5, 7, 18, 20	3, 4, 5, 18	
B6	3, 4, 6, 10, 13, 18	3, 4, 5, 6, 7, 18, 20	3, 4, 6, 18	
B7	3, 4, 5, 6, 7, 10, 13, 18, 20	3, 4, 7	3, 4, 7	
B10	10, 18	3, 4, 5, 6, 7, 10, 13	10	
B13	3, 4, 10, 13, 18	3, 4, 5, 6, 7, 13, 20	3, 4, 13	
B18	3, 4, 5, 6, 18	3, 4, 5, 6, 7, 10, 13, 18, 20	3, 4, 5, 6, 18	IV
B20	3, 4, 5, 6, 13, 18, 20	7, 20	20	

Table AIII.
Iteration 4

Barriers	Reachability set	Antecedent set	Intersection set	Level
B3	3, 4, 5, 6, 7, 10, 13	3, 4, 5, 6, 7, 13, 20	3, 4, 5, 6, 7, 13	
B4	3, 4, 5, 6, 7, 10, 13	3, 4, 5, 6, 7, 13, 20	3, 4, 5, 6, 7, 13	
B5	3, 4, 5, 6, 10, 13	3, 4, 5, 7, 20	3, 4, 5	
B6	3, 4, 6, 10, 13	3, 4, 5, 6, 7, 20	3, 4, 6	
B7	3, 4, 5, 6, 7, 10, 13, 20	3, 4, 7	3, 4, 7	
B10	10	3, 4, 5, 6, 7, 10, 13	10	V
B13	3, 4, 10, 13	3, 4, 5, 6, 7, 13, 20	3, 4, 13	
B20	3, 4, 5, 6, 13, 20	7, 20	20	

Table AIV.
Iteration 5

Barriers	Reachability set	Antecedent set	Intersection set	Level
B3	3, 4, 5, 6, 7, 13	3, 4, 5, 6, 7, 13, 20	3, 4, 5, 6, 7, 13	VI
B4	3, 4, 5, 6, 7, 13	3, 4, 5, 6, 7, 13, 20	3, 4, 5, 6, 7, 13	VI
B5	3, 4, 5, 6, 13	3, 4, 5, 7, 20	3, 4, 5	
B6	3, 4, 6, 13	3, 4, 5, 6, 7, 20	3, 4, 6	
B7	3, 4, 5, 6, 7, 13, 20	3, 4, 7	3, 4, 7	
B13	3, 4, 13	3, 4, 5, 6, 7, 13, 20	3, 4, 13	VI
B20	3, 4, 5, 6, 13, 20	7, 20	20	

Table AV.
Iteration 6

Barriers	Reachability set	Antecedent set	Intersection set	Level
B5	5, 6	5, 7, 20	5	
B6	6	5, 6, 7, 20	6	VII
B7	5, 6, 7, 20	7	7	
B20	5, 6, 20	7, 20	20	

Table AVI.
Iteration 7

Barriers	Reachability set	Antecedent set	Intersection set	Level
B5	5	5, 7, 20	5	VIII
B7	5, 7, 20	7	7	
B20	5, 20	7, 20	20	

Table AVII.
Iteration 8

Barriers	Reachability set	Antecedent set	Intersection set	Level	
B7	7, 20	7	7		Table AVIII. Iteration 9
B20	20	7, 20	20	IX	

Barriers	Reachability set	Antecedent set	Intersection set	Level	
B7	7	7	7	X	Table AIX. Iteration 10

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