Managing supply chains for sustainable operations in the era of Industry 4.0 and circular economy: Analysis of barriers

Abstract

Organizations are struggling to leverage emerging opportunities for maintaining sustainability in the global markets due to many barriers in the era of Industry 4.0 and circular economy. The main aim of this study is to analyze these barriers to improve the sustainability of a supply chain. Our study identifies the major criteria for sustainable operations and barriers that need to be overcome to achieve the objectives of sustainability through literature review and experts' opinions. An integrated approach comprising Analytic Hierarchy Process (AHP) and Elimination and Choice Expressing Reality (ELECTRE) is used to analyze these barriers and ensure the sustainable supply chain operations. Resource circularity, increasing profits from green products, and designing processes for resource and energy efficiency have been found to be as major sustainability criteria.

There are many barriers to the implementation of Industry 4.0. These barriers include but are not limited to, a lack of a skilled workforce that understands Industry 4.0, ineffective legislation and controls, ineffective performance framework, and short-term corporate goals. The study finds that ineffective strategies for the integration of industry 4.0 with sustainability measures, combined with a lack of funds for industry 4.0 initiatives, are just two of the major barriers. The findings of the study will help organizations to develop an effective and integrated strategic approach that will foster sustainable operations through the utilization of improved knowledge of Industry 4.0 and the circular economy.

Keywords: Industry 4.0, Circular Economy, Sustainability, Barriers, AHP, ELECTRE

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1. Introduction

The increasing population, a growing economy, and an improved lifestyle of people have increased the exploitation of natural resources. Preston and Herron (2016) observed that the demand for these natural resources has been growing steadily. Due to this increasing demand for natural resources, organizations are facing many operational challenges. The shortage of resources is resulting in increased input costs and as a consequence products are less sustainable in the market (Preston and Herron, 2016). Most manufacturing organizations are still working on the traditional linear economy model (Singh et al., 2020). The conventional approach of reuse and recycling of materials is not much cost-effective and leading to wastage of valuable resources.

Global supply chains are facing extensive pressure from regulatory bodies to become sustainable across all operational activities (Vanalle et al., 2017). Environmental and social concerns are forcing organizations to transition from linear to circular processes to halt the unproductive disposal of consumer or end of life products. The Circular Economy (CE) approach consists of the 3Rs (Reduce, Reuse, and Recycle). The 3R's system is used as a tool to improve sustainability within operations (Sauve et al., 2016). CE enables more effective use and reuse resources by employing competent design and manufacturing processes.

Technology has emerged as an important driver of sustainable operations (Dubey et al., 2017). Organizations must exploit emerging technologies to make operations environmentally-friendly and economically feasible. Wang et al. (2016) observed that some Industry 4.0 based technologies can make operations sustainable. These are the Internet of Things (IoT), Cloud Manufacturing (CM), Cyber-Physical Systems (CPS), and Additive Manufacturing (AM) (Hozdie, 2015).

Using the combined approach of Industry 4.0 and CE, resources can be utilized multiple times for different purposes (Stock and Seliger, 2016). Many Indian organizations have started using Industry 4.0 based technologies such as IoT, machine learning and blockchain that have been found to improve the process efficiency. For example, Tata Power Ltd has created a digital platform to aid its customers to better manage power consumption with real-time data and improve the efficiency of power plants. Voltas Ltd is using IoT based solutions to offer their customers a superior chiller maintenance service.

Lin (2019) observed that Industry 4.0 based technologies may help to foster a more suitable decision-making process and facilitate smart production for CE. Dubey et al. (2017) state that through effective integration of Industry 4.0 and sustainability measures, organizations can develop world-class sustainable manufacturing systems. It has been observed that the implementation and usage of digital technologies can overcome various challenges of CE (Singh et al., 2019). Many organizations, however, are not sufficiently able to exploit their potential for sustainable growth in a globalized market because they lack awareness of the basic principles that are the foundation of resource circularity and Industry 4.0.

Past studies have not made any attempt to pursue the analysis of the barriers for sustainable operations within the context of CE and Industry 4.0. Singh et al. (2019) and Dubey et al. (2017) have posited that very little literature on the integration of Industry 4.0 and CE is available and that most studies have analyzed the barriers that impede CE and Industry 4.0 separately.

With this in mind, this study addresses the following research objectives:

- Identification of criteria for sustainability in the context of CE.
- Identification of barriers for sustainable operations in the era of Industry 4.0 and CE.
- Mapping of these barriers of sustainable operations.

The main goal of the study is to identify the ranking of different barriers that impede sustainable operations of a supply chain in the context of Industry 4.0 and CE. A positive argument can then be made in favour of sustainable digitized manufacturing processes. The findings may also help industry professionals to exploit emerging business opportunities by managing barriers and challenges.

The organization of the remaining part of this paper is as follows: Literature review of industry 4.0 and sustainability parameters of CE is presented in Section 2. The research methodology comprising of AHP and ELECTRE is detailed in Section 3. The results are presented in Section 4 and the practical and theoretical implications of this study are discussed in Section 5. Finally, Section 6 provides the conclusions of the study including its limitations and potential directions for future research.

2. Literature Review

Within the field of industrial research, two major trends have emerged in recent years: Industry 4.0 and the CE.

Industry 4.0 has led to a wave of technology that drives the digitization of operations (Jabbour et al., 2018a). Digital communication along the whole value chain, or the flow of the data, is termed ‘digital threads’ (Nanry et al. 2015), and these simplify the business processes.

CE is based on the closed-loop design of the production system and leads to an increase in the efficiency of resources. This study will map the barriers that hinder sustainable operations in an era of Industry 4.0 and CE. The literature review in the following sub-sections discusses different opportunities and challenges that arise in the emerging business environment of Industry 4.0 and CE.

2.1 Industry 4.0: Opportunities and Challenges

The term “Industry 4.0” was first coined at a trade fair organized in Hannover, Germany in 2011 (Kagermann et al. 2015). Industry 4.0 technologies can assist companies to achieve integrated, flexible, and diversified production systems that will lead to the production of customized products (Li et al., 2017; Thoben et al., 2017). Organizations can allocate resources efficiently on a real-time basis by employing Industry 4.0 technologies.

The IoT, cloud manufacturing, cyber-physical systems and AM are four major components of Industry 4.0 (Jabbour et al., 2018a). The cyber-physical system is the integration of cyberspace, physical systems, objects and machines or devices that form a network that obtains real-time data enabling the decision-making process for prioritization of production orders, maintenance requirements, and optimization of tasks (Lee et al., 2015). The IoT facilitates collection and transmission of data among different devices and objects (Li et al., 2017): Radio Frequency Identification (RFID), bar-coding and wireless sensors are just some technologies that form part of the IoT (Zang et al., 2017). Cloud manufacturing provides information concerning the availability and sharing of manufacturing resources (Liu and Xu, 2017).

With the application of IoT, companies collect and manage big data that enable effective decision making. For example, business applications for improving the response of mobile taxis (Lanza et al., 2015) and the reduction of energy consumption in manufacturing and service processes (Tao et al., 2016).

Cloud computing has various industrial applications such as monitoring the mobility of transportation management systems (Nowicka, 2016) and calculating carbon footprint (Singh et al., 2015). Artificial intelligence may improve the effectiveness of energy management (Zahraee et al., 2016) and Shivajee et al. (2019) observed that by using IT-enabled quality tools and monitoring their processes continuously, organizations were able to reduce their manufacturing conversion cost.

Many organizations are unable to implement Industry 4.0 technologies because of the poor leadership style (Shao et al., 2017). For successful implementation of Industry 4.0 technologies that promote the sustainable performance of organizations, senior management should be both inspiring and transformational (Politis, 2001). Senior management support is vital for making changes regarding processes and performance (Young and Jordan, 2008). The application of technologies should be strategically aligned with the long-term goals of an organization. Indeed, a lack of effective strategic integration of Industry 4.0 with sustainability goals may lead to the failure of an organization (Kahn et al., 2012). Absence of alignment between Industry 4.0 technologies and CE criteria has been observed as a source of difficulty for sustainable operations (Ball et al., 2018) and it may also result in the making of unsustainable manufacturing decisions.

Successful implementation of emerging technologies requires a skilled workforce and to this effect, employees should be trained to meet emerging challenges found within sustainable operations and Industry 4.0 technologies (Waibel et al., 2017; Jabbour and Jabbour, 2016; Sarkis et al., 2010). Successful implementation will help to reduce employees' resistance to change from a linear economy approach to one of CE. Organizational culture should motivate employees to remain updated about emerging technologies and future challenges (Jabbour and Jabbour, 2016). Many organizations lack the ability to take initiatives for upgrading technological processes which would make them sustainable and more competitive. This is due to a lack of awareness surrounding the potential of Industry 4.0 technologies and CE.

Jabbour et al. (2018a) also observed that organizations may not implement Industry 4.0 technologies because of the absence of senior management support, ineffective strategies, poor workforce skills, lack of funds for investment and, again, insufficient information regarding Industry 4.0. Several other market barriers hindering sustainable operations are lower cost of virgin materials, costly recycling process, lower profit margin of green products and poor market demand (Mont et al., 2017; Preston, 2012).

There are various constraints that hamper the technological ability of an organization to fulfil its sustainability potential. For example, altering a linear economy to CE is expensive and can take an inordinate amount of time. Many organizations are not able to implement new technologies such as IoT, cloud computing and big data analytics due to fear of misinvestment (Ranta et al., 2018). Effective handling of barriers to sustainable manufacturing operations is crucial (Luthra et al., 2015).

Through a literature review and experts opinion, fifteen important barriers are identified within this study and these barriers are summarized in Table 1.

Table 1. Barriers to sustainable operations of supply chains.

S. No.	Barriers for Sustainable Operations of supply chain	References	Remarks
B1	Risk of misinvestment	Müller et al. (2017), Moser et al. (2017), Ranta et al. (2018).	A large investment is required for procuring the Industry 4.0 technologies. Investors worry about the implications of misinvestment.
B2	Insufficient legislation & control	Kamble et al. (2018), Oesterreich and Teuteberg (2016), Raj et al. (2019), Muduli et al. (2013).	Insufficient legislation and control over the small and medium enterprises and ancillary companies have served to ensure that management is reluctant to utilize new technologies for sustainable operations.
B3	Insufficient strategy for integration of Industry 4.0 & C.E	Ball et al., (2018), Rajput and Singh (2019); Kahn et al. (2012), Kiel et al., (2017a, 2017b), Kamble et al. (2018); Jabbour et al. (2018b).	A well-defined strategy is required to understand why Industry 4.0 should be implemented and how implementation can be fulfilled. The strategy may overcome a major hurdle regarding the integration of Industry 4.0 technologies with the concept of the circular economy.
B4	Lack of skilled workforce	Waibel et al. (2017); Jabbour and Jabbour (2016); Sarkis et al. (2010); Erol et al. (2016), Müller and Voigt (2017), Kiel et al. (2017a, 2017b).	Successful application of new technology requires a specialized workforce. Lack of skills may be treated as a barrier that impedes this implementation.
B5	Lack of	Kulatunga et al. (2013);	The investment required for Industry

	funding for Industry 4.0	Erol et al. (2016), Kiel et al. (2017a, 2017b), Müller and Voigt (2017), PWC (2014), Mittal et al. (2018), Kumar et al.(2020)	4.0 technologies is very high. Lack of funds is a barrier to the implementation of Industry 4.0 technologies.
B6	Ineffective performance framework	Sarkis (2012), José et al. (2017), Batista et al. (2018).	The ineffective performance framework displays a lack of planning and policy for implementation and measuring performance of the systems.
B7	Use of materials as energy	Braungart et al. (2007), Benyus (2003).	Technology is required for recycling waste materials and to utilize them as renewable materials. Some material can be also used as alternative sources of energy.
B8	Lack of waste management	Pourjavad and Shahin (2018), Sharma et al. (2017); Sarkis (2003).	Recycling, reuse and re-manufacturing are the major components of CE. Lack of waste management creates a hurdle in front of fulfilling the requirements of the CE.
B9	Poor resource/ infrastructure quality	Xu et al. (2018), Batista et al. (2018), Ghadimi et al. (2019), Geng et al. (2017), Sharma et al., (2017).	High quality of infrastructure and sufficient resources are required for successful implementation of industry 4.0 technologies.
B10	Lack of Govt. support	Prakash and Barua (2015), Govindan et al. (2013), Moktadir et al. (2018).	There are a plethora of rules and regulations for waste minimization and eco-friendly manufacturing activities but the government fail to encourage process automation through Industry 4.0 technologies.
B11	Employees resistance to change	Jabbour and Jabbour (2016), Luthra et al. (2019), Kiel et al. (2017b), Haddud et al. (2017).	The employees may resist changes due to fear of loss of jobs: the automation may eliminate many activities that are normally performed manually.
B12	Insufficient market demand	Mont et al. (2017), Preston (2012), Lin et al. (2013).	Due to higher processing and manufacturing cost of green products, market demand is not sufficient. Thus, marketing of green, refurbished and recycled products is a major barrier for sustainable operations of the supply chains.
B13	Lack of management support	Turker and Altuntas (2014), Horváth and Szabó (2019), Ghadimi et al. (2019), Young and Jordan, (2008), Jabbour et al. (2018a).	Due to lack of vision and also lack of finance, senior management is often reluctant to support activities for sustainable operations.

B14	Short term goals	Giunipero et al. (2012), Kambli et al. (2018), Moeuf et al. (2018).	In most cases, the management has short term goals and they require immediate output. Therefore, organizations are hesitant to invest financially in CE and Industry 4.0.
B15	Lack of awareness of Industry 4.0	Luthra and Mangla (2018), Jabbour et al. (2018a), Hofmann and Rüsch (2017).	Many organizations are not aware of the benefits to be gained from implementing Industry 4.0 and CE concepts, hence they lack motivation for the change.

2.2 Circular Economy and Sustainable operations

Stahel and Reday (1976) were the first to introduce the term CE. CE comprises a regenerative system based on the philosophy of zero waste, the concept being that waste produced within an organization has the potential to be utilized as a valuable resource by another organization. Geng and Doberstein (2008) describe CE as "realization of closed-loop material flow in the whole economic system". Webster (2015) state that "CE is one that is restorative by design, and which aims to keep products, components, and materials at their highest utility and value, at all times".

Some of the most important components of CE within the literature are performance economy (Stahel, 2010), industrial ecology (Lifset and Graedel, 2001), cradle-to-cradle design (Braungart et al., 2007), product-service systems (Tukker, 2015), natural capitalism (Hawken et al., 2008), industrial symbioses (Chertow and Ehrenfeild, 2012), biomimicry (Benyus, 2003), circular flow of materials (Lieder and Rashid, 2016), industrial ecosystems (Jelinski et al., 1992), eco-efficiency (Haas et al., 2015), regenerative design (Lyle, 1994), zero emissions, industrial ecology (Graedel and Allenby, 1995), etc.

The cradle-to-cradle model uses a material reuse principle. In this model, industrial materials can be classified as technical or biological nutrients. Technical nutrients are considered as non-toxic, non-hazardous synthetic materials that can be utilized repeatedly, biological nutrients are organic materials that decompose without affecting the natural environment and biomimicry systems imitate the nature of the innovation in process and product design.

Using CE, the material value can be maintained for a long time; the sustainability of operations is an essential requirement of CE (Kazancoglu et al., 2018). Operations sustainability can be judged by measuring different kinds of emissions. For example, SO_2, NO, effluent and solid wastes, hazardous and toxic material consumption (Paulraj et al., 2017, Zhu et al., 2017). Sustainability is assured through the implementation of reverse logistics and other resource circularity practices within a supply chain (Pourjavad and Shahin, 2018; Sharma et al., 2017; Sarkis, 2003). Organizations should also develop a capability to improve resource efficiency, product quality and decreased scrap that will aid the sustainability of operations (Geng et al., 2017; Sharma et al., 2017). It is safer to produce environmentally-friendly products of consistent quality and regular use. The green-design of products minimizes energy consumption and waste disposal (Foo et al., 2018; Jabbour and Jabbour, 2016) but green products require green materials and degradable/reusable packaging materials to protect the environment (Wu et al., 2015). Papadopoulos and Giama, (2007) emphasized the implementation of certification and accreditation based on the use of the 3Rs (recycling, reuse, and reduction) in supply chain operations. A sustainable supply chain not only boosts community welfare initiatives, but also decreases cost, increases market share and resource efficiency, sales, and profit margin and employees' motivation and satisfaction (Younis et al., 2016). The literature review identifies some of the major sustainability criteria in Table 2.

Table 2. Sustainability parameters in the context of the circular economy.

S. No.	Sustainability Parameters	References	Remarks
C1	Resource Circularity	Figge et al. (2018), Stock and Seliger (2016), Lieder and Rashid (2016), Linder et al. (2017).	Resource circularity is based on the concept of cradle-to-cradle and biomimicry. It aids the elimination of waste.
C2	Cost-saving through product quality	Yeow and Sen (2006), Shivajee et al. (2019); Rust et al. (2002).	Improved quality reduces the cost of scrap, shutdown, inspection, and testing, etc. Thus, these costs can be lessened by improving the quality of the systems.
C3	Decreasing emission	Singh et al. (2015), Graedel and Allenby (1995), Paulraj et al. (2017), Zhu et al. (2017).	Decreasing emission is one of the criteria for evaluating the effectiveness of sustainable operations.
C4	Waste reduction & pollution monitoring	Heck and Rogers (2014), Geng et al. (2012).	Waste in the various forms (Waste materials, packaging materials, wastewater, and gaseous emission) is to be reduced and pollution must be monitored properly for sustainability.
C5	Process design for resource and	Towler (1996), Tao et al. (2016), Zahraee et al.	The circular economy leads to the highest utility of products,

	energy efficiency	(2016).	components, and energy since it is restorative and regenerative by design.
C6	Increasing profit from green products	Foo et al. (2018); Jabbour and Jabbour (2016).	For market survival of green products, the profit margin should be high. Reducing product cost leads to an increase in product demand.
C7	Improving green logistics	Kazancoglu et al. (2018), Zeng et al. (2017).	All green practices such as the use of green packaging materials, low emission of the vehicle, proper maintenance of the vehicle are a part of green logistics.
C8	Improved employees and community health	Younis et al. (2016), Moldavska and Welo (2017), Barnidge et al. (2011).	This is concerned with social sustainability. The proper care of employees and community health are part of corporate social responsibility.
C9	Improving green purchasing	Moktadir et al. (2018), Tseng et al. (2019), Yadav et al. (2020).	It means to purchase green materials, components, and sub-components and services for producing the goods and services.

The proposed framework for mapping of barriers restricting sustainable operations of supply chains in the era of Industry 4.0 and CE is shown in Figure 1. This framework summarizes four Industry 4.0 based technologies: Cyber-Physical Systems, IoT, Cloud manufacturing, and AM and will include some major barriers that block the implementation of these technologies as discussed in the previous section. CE can be summarized by using four fundamental principles: cradle-to-cradle, biomimicry, industrial ecology and blue economy covering nine sustainability parameters.

Based on the literature review, the authors have identified the following gaps:

(i) Most of the literature available on the circular economy is based on the philosophy and benefits of CE. Further study is therefore needed to look at feasibility related issues in the implementation of CE.

(ii) Most of the studies have analyzed issues related to Industry 4.0 and the circular economy in isolation. Therefore, study integrating Industry 4.0 concepts with a CE is required.

(iii) The authors have determined the barriers that burden the implementation of green supply chains and advanced manufacturing technologies in isolation. This leads to further study of the barriers that impede sustainable operations in the current business environment of Industry 4.0 and CE.

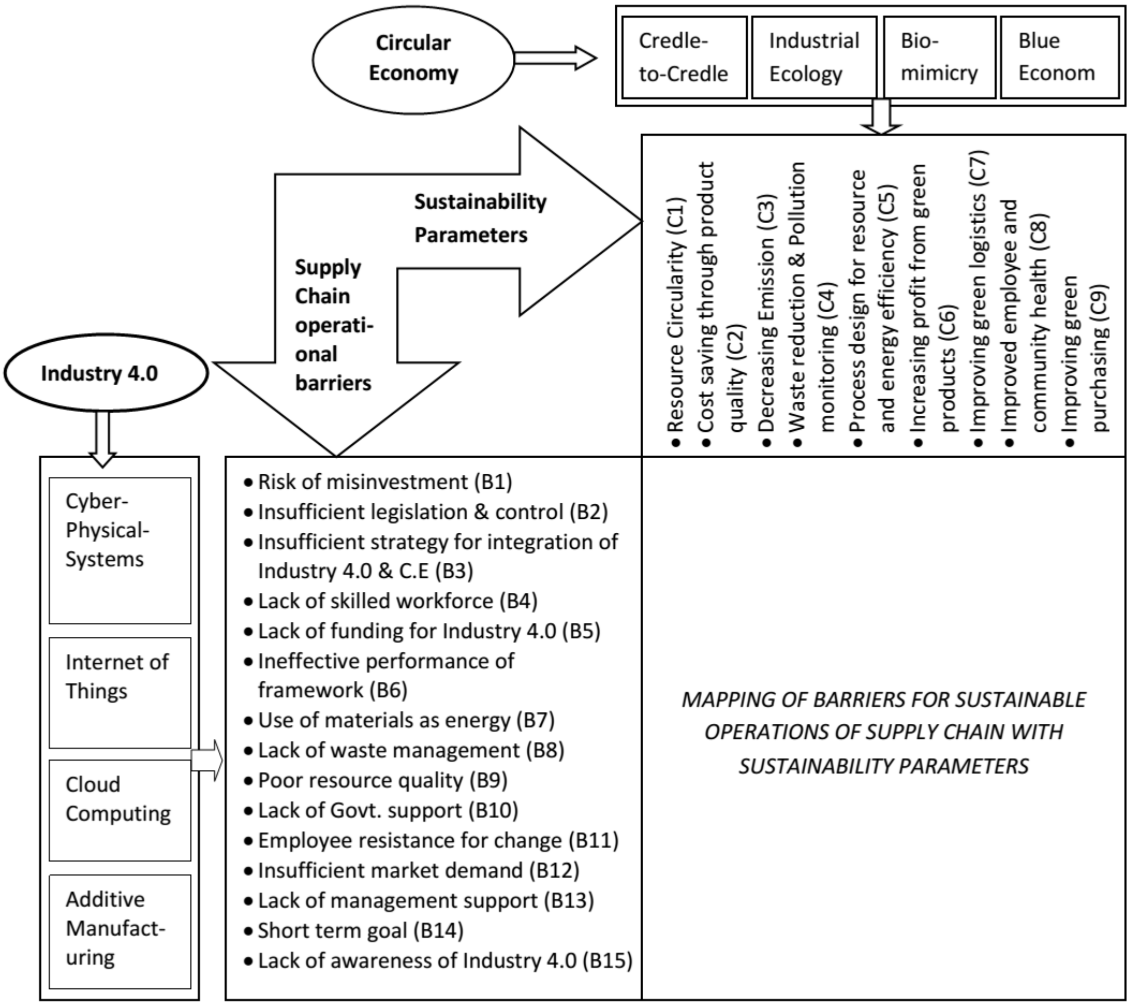

Figure 1: Mapping of barriers that impede sustainable operations in the era of Industry 4.0 and CE.

3. Research Methodology

In the literature, several multi-criteria decision-making (MCDM) tools have been used, all of which have advantages and disadvantages. Within this study, an AHP and ELECTRE integrated approach is implemented for the analysis. The AHP method is preferred by many researchers due to the possibility of applying both qualitative and quantitative criteria. It has effective traceability of the decision and assures quality using consistency indices

(Tscheikner-Gratle et al., 2017). However, AHP suffers from rank reversals in the case of addition and removal of the criteria and alternatives within the decision model. This can be prevented by prohibiting the user from using the addition and removal of criterion and any alternatives from the decision model (Hodgett, 2016).

Similarly, ELECTRE also has some advantages and disadvantages. According to Li and Wang (2007), the weakness of the normal ranking of ELECTRE is that it requires an additional threshold to be introduced. The ranking of the alternatives depends upon the size of the threshold, for which there exists no 'correct' value. On the other hand, Sabaei et al. (2015) mentioned that "the main advantage of the method is that ELECTRE can handle both quantitative and qualitative data for outranking alternatives with high uncertainty". ELECTRE is also less sensitive to changes in data compared to other methods. Considering the above facts, the combination of the AHP and ELECTRE model is found to be more accurate than the individual model of ranking. ELECTRE is used in this study.

The barriers that hamper sustainable operations of supply chains are mapped within this study to sustainability parameters of CE as shown in Figure 1. The importance of the ranking of criteria for sustainable operations has been found using AHP. The weights during pairwise comparisons between criterion are based on the expert consensus that took place during the discussion. Finally, ELECTRE is used to find the rank of the barriers of sustainable operations of supply chains within the CE environment.

The research methodology is next discussed in two parts. The first part discusses the steps of AHP and the second part discusses the principles underpinning ELECTRE.

3.1 Analytic Hierarchy Process: AHP helps decision-makers to analyze the relative importance of criterion to implement effective decision-making (Saaty, 1980). AHP is found to be more advantageous in comparison to ANP because of lower pairwise comparisons regarding the lesser hierarchy problem. In this study, AHP has been used for ranking the parameters of CE. These criteria are compared with each other on the Saaty's (1980) nine-point rating scale. The calculation procedure of AHP is summarized below:

- Define the problem and objective.
- Divide the problems in the form of a hierarchy (from objective to the lower- level).
- Undertake pairwise comparison using Saaty's 9-point rating scale for each lower level.
- Check the consistency ratio.

- Estimate the relative rating of the component at each level.

Relative ranking of sustainability criteria received by AHP is used in the next stage of this study concerned with the ranking of barriers (Table 3).

3.2 Elimination and Choice Expressing Reality (ELECTRE): ELECTRE is used to rank the barriers for sustainable operations of supply chains in the context of Industry 4.0. Decision making can be undertaken by adopting AHP. MCDM, however, gives superior results when integrated with other decision-making tools (Kang and Park, 2014). Kumar and Singh (2020) used the integrated model of AHP and ELECTRE for evaluating alternative solutions for crop residue burning. Roy (1991) proposed the ELCTRE method in 1965 for ranking and outranking of alternatives. The applications of ELECTRE have also been reported in a plethora of articles that include its fuzzification (Kumar et al., 2017a; Kumar et al., 2017b; Kumar et al., 2016).

Using the ELECTRE process, the barriers are rated against the sustainability criterion on the five-point rating scale. These ratings are normalized and a weighted normalized matrix is formed. The concordance and discordance matrices are prepared from the weighted matrix based on the threshold, defined in the ELECTRE method. These concordance and discordance matrices are converted into the Boolean matrix and the elements of these Boolean matrices are multiplied, forming a Dominance matrix. These barriers of sustainable operations in the supply chain are ranked based on the Dominance matrix. The detailed calculation steps of ELECTRE (Shanian and Savadogo, 2006) are mentioned in the Appendix (Equation A1 to A12).

4. Results

The analysis within the study is based upon the expert opinions of employees within companies located in Delhi NCR, India. A large number of small and medium scale enterprises have established their plants in Delhi NCR. The national capital region, comprising the states of Delhi, some parts of Haryana, Uttar Pradesh and Rajasthan, produce on average 30% of the total auto components produced throughout the country. The primary industrial sector locations within the NCR are Delhi, Gurgaon, Manesar, Bhiwadi, Meerut, Ghaziabad, Faridabad, Kundli, Sonepat, Murthal, Gautam Budh Nagar, Bulandshahr, and Panipat.

Maruti Udyog Limited, also located in Delhi NCR, is the largest car manufacturer in India along with other major auto sector companies, including Honda Motors and Hero MotoCorp. This region is also home to many electronics companies such as Samsung Electronics and Oppo mobiles Pvt Ltd.

A team comprising five experts was put together to undertake pairwise comparisons of different criterion. Three experts were experienced in the industry and had more than ten years' experience regarding sustainability-related issues. The remaining two experts were academicians working in the area of sustainability.

Nine sustainability parameters of CE and fifteen barriers impeding sustainable operations have been identified within this study through literature review and experts' opinions. The proposed framework for analyzing barriers prohibiting sustainable operations is shown in Figure 1. Initially, the pairwise comparison matrix of the criterion has been prepared based on a 9-point rating scale using AHP as discussed in the research methodology section. The importance ratings of criterion using pairwise comparison are shown in Table 3.

Table 3: Pairwise Comparison of Criteria for Importance Rating

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**Weights**	**Rank**
C1	1	4	5	3	2	3	7	6	7	0.297	1
C2	0.25	1	2	3	0.5	0.5	4	5	5	0.131	4
C3	0.2	0.5	1	0.25	0.33	0.5	2	2	3	0.061	6
C4	0.33	0.33	4	1	0.5	0.33	3	2	3	0.091	5
C5	0.5	2	3	2	1	0.33	5	3	4	0.144	3
C6	0.33	2	2	3	3	1	2	2	2	0.16	2
C7	0.14	0.25	0.5	0.33	0.2	0.5	1	0.5	2	0.037	8
C8	0.17	0.2	0.5	0.5	0.33	0.5	2	1	2	0.047	7
C9	0.14	0.2	0.33	0.33	0.25	0.5	0.5	0.5	1	0.031	9

Number of comparisons = 36; Consistency Ratio CR = 7.5%; Principal Eigen value = 9.873; Eigenvector solution: 6 iterations, delta = 2.1E-8

After finding the importance rating of the sustainability criterion, a decision matrix (Table 4) of different barriers hampering sustainable operations of supply chains using a five-point rating scale has been prepared using Equation (A1).

Table 4: Decision matrix (Rating of barriers for sustainable operations)

	WEIGHT	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**	**B13**	**B14**	**B15**
C1	**0.297**	4	4	5	5	4	5	3	3	3	4	4	3	3	4	3
C2	**0.131**	3	2	3	3	3	2	3	3	4	2	2	2	2	4	3

C3	**0.061**	3	3	3	3	2	3	2	5	2	3	4	2	2	3	2
C4	**0.091**	3	4	3	3	3	4	4	4	4	3	4	3	3	3	3
C5	**0.144**	3	4	4	5	3	5	4	4	4	3	4	3	3	3	3
C6	**0.160**	3	3	2	2	2	2	3	2	3	2	2	2	2	4	2
C7	**0.037**	2	2	4	2	3	2	2	3	2	3	3	2	2	2	2
C8	**0.047**	2	2	2	2	2	2	2	2	2	3	2	2	2	3	4
C9	**0.031**	2	2	2	2	2	2	2	2	2	3	2	2	2	2	2

Normalization of the decision matrix is required to ensure its elements are on the same scale, the scale being from 0–1. Normalization is undertaken using equation (A2). After normalization, the weighted normalized matrix is produced by multiplying the elements with the corresponding weights of the criterion using equation (A3). The concordance and discordance sets of criteria are segmented for all the barriers from the weighted normalized matrix using the conditions in equations (A4) and (A5) respectively. Now, the concordance matrix is developed from the summation of the concordance criterion as mentioned in Equation (A6). The discordance matrix is developed using equation (A7). The concordance matrix is converted into a Boolean Matrix E using the threshold as mentioned in equations (A8) and (A9). The discordance matrix is converted into Boolean Matrix F using the threshold in equations (A10) and (A11). Finally, a dominance matrix G is formed by multiplying the corresponding elements of the Boolean Matrices E and F as shown in Table 5.

Table 5: Global Matrix (Dominance matrix)

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
B1	-	0	0	0	1	0	1	0	0	1	0	1	1	0	1
B2	0	-	0	0	0	0	1	1	0	1	1	1	1	0	0
B3	0	0	-	0	1	0	1	1	0	1	1	1	1	0	0
B4	0	0	0	-	1	1	1	1	0	1	1	1	1	0	1
B5	0	0	0	0	-	0	0	0	0	1	0	1	1	0	1
B6	0	0	0	0	1	-	1	1	1	1	1	1	1	0	1
B7	0	0	0	0	0	0	-	0	0	0	0	1	1	0	1
B8	0	0	0	0	0	0	0	-	0	0	0	1	1	0	1
B9	0	0	0	0	0	0	1	0	-	0	0	1	1	0	1
B10	0	0	0	0	0	0	0	0	0	-	0	1	1	0	1
B11	0	0	0	0	0	0	0	1	0	1	-	1	1	0	1
B12	0	0	0	0	0	0	0	0	0	0	0	-	1	0	0
B13	0	0	0	0	0	0	0	0	0	0	0	1	-	0	0
B14	1	1	0	0	1	0	1	0	1	1	0	1	1	-	1
B15	0	0	0	0	0	0	0	0	0	0	0	1	1	0	-

The Boolean value 1 indicates that the i^{th} barrier outranks the j^{th} barrier, here, '*i*' indicates the row and '*j*' indicates the column. For example, in row 2 of Table 5, barrier B2 outranks the barriers B7, B8, B10, B11, B12, and B13. It means that barrier B2 will be ranked higher than the barriers B7, B8, B10, B11, B12, and B13 for the importance. Similarly, all barriers are ranked. Based on the dominance matrix G, the ranks are provided to the barriers for their importance in sustainable operations of supply chains as shown in Table 6.

Table 6: Rank of the barriers for sustainable operations in the circular economy

Barriers	Outranking Barriers	Rank
B1	B5, B7, B10, B12, B13, B15	4th
B2	B7, B8, B10, B11, B12, B13	4th
B3	B5, B7, B8, B10, B11, B12, B13	3rd
B4	**B5, B6, B7, B8, B10, B11, B12, B13, B15**	**1st**
B5	B10, B12, B13, B15	6th
B6	**B5, B7, B8, B9, B10, B11, B12, B13, B15**	**2nd**
B7	B12, B13, B15	7th
B8	B12, B13, B15	7th
B9	B7, B12, B13, B15	6th
B10	B12, B13, B15	7th
B11	B8, B10, B12, B13, B15	5th
B12	B13	9th
B13	B12	9th
B14	**B1, B2, B5, B7, B9, B10, B12, B13, B15**	**2nd**
B15	B12, B13	8th

5. Discussion and Implications

It has been observed that the barrier B4 that the lack of skilled workforce is ranked as the most important barrier in the way of achieving sustainable operations of supply chains. A skilled workforce is required to implement Industry 4.0 technologies and integrate them with the sustainability criteria of CE. Agyemang et al. (2019) observed that lack of expertize is one of the important barriers in the application of a circular economy but, they found it as 3rd important barrier. They have found the unawareness of employees is the top-ranked barrier, but in our analysis, it is a lower-ranked barrier. Ensuring that the employees are kept up to date with skills is a major driver for any new initiative, such as implementation of new technology in an organization. Jabour et al. (2018b) have also emphasized the use of technology for the implementation of CE. However, before using the new technology, awareness and training of the employees should be given priority.

The barriers B6 and B14, for example, ineffective performance framework and short-term goals, are jointly ranked as second important barriers. The performance framework should be designed in such a way that it evaluates the performance of the supply chains in the context of CE and Industry 4.0.

Govindan and Hasanagic (2018) have also considered the ineffective circular economy framework as a barrier. The framework should have detailed planning and policy of the management for the implementation of the circular economy. To make it effective, the management must review the plan and policy continuously as per the needs and feedback of the organization.

Most organizations focus on the short-term goal (B14), for example, earning profit by compromising product quality and process sustainability. The short-term goal of the management may be linked to the financial constraint of the organization. Financial constraint is one of the important barriers in the implementation of Industry 4.0 and CE. For longer survival of society and the country, a clear vision of economic and environmental sustainability is required. The government should frame policies to incentivize investment initiatives. The goal must be long term and include further expansion of the business activities incorporating the dimensions of CE.

The barrier B3 (ineffective strategy for integration of industry 4.0 with CE) is the third important barrier. In most cases, it has been observed that the purpose of industry 4.0 is to automate the processes for the optimization of their resource utilization and to increase productivity. Kirchherr et al. (2017) have also observed that a lack of policies for supporting the transition from a linear economy to CE is also a regulatory barrier. The new technology must be focused on the digitization of the processes and consider the sustainability dimensions of CE, for example, resource circularity.

The fourth important barriers for the sustainable operations of supply chains are B1 and B2 (Risk of misinvestment and insufficient legislation and control). The fear of the risk of misinvestment is due to a lack of vision from management and lack of awareness regarding the benefits of CE in the long-term. Insufficient legislation and control also lead to the reluctant attitude of the management towards sustainability.

The fifth important barrier is B11 (Employee resistance to change). Employees have the impression that new technologies may put their jobs at risk. To this end, employees should be made aware of long term benefits coming from such initiatives for the organization and be reassured that such initiatives will not pose any risk to their employment.

The resistance from the employees to such initiatives can be overcome by instigating appropriate motivation and encouraging employees to engage.

The remaining barriers are also important and need to be addressed properly. Most of these are the result of reluctance to instigate change by the management, lack of awareness of the employees, ineffective legislation and control of the supply chain activities. Therefore, management should involve its employees in all such initiatives for achieving goals of CE and Industry 4.0.

5.1 Practical Implications*:* The findings of the study may help industry professionals to focus the efforts to digitize or automate the systems in the context of sustainability or resource circularity. Resource conservation is very important in the present context of the CE. It will also lead to saving the environment. The study also improves our knowledge of the various barriers in the sustainable operations of the entire supply chain. When the priority ranking of the different barriers are known, management should develop an effective action plan for sustainable operations in the present business environment of CE and Industry 4.0. Organizations need to integrate principles of CE and Industry 4.0 in their manufacturing processes for being competitive and sustainable. Performance frameworks should be designed considering the requirements of CE and Industry 4.0.

5.2 Theoretical Implications: By highlighting the barriers to sustainable operations of the supply chain in context to Industry 4.0 and CE, researchers/academics may be motivated to explore and validate possible solutions to remove barriers in different contexts. The priority of different barriers will help academics and researchers to propose strategies for sustainable growth of organizations in the dynamic business environment. Researchers will also be able to explore the requirements of newer skills and knowledge as per the current requirement of the industry. The findings will also help in proposing and validating a comprehensive performance framework for ensuring sustainable operations.

5.3 Implication for Policymakers: Government policies play a crucial role in creating an environment for sustainable operations. Policies may differ from country to country and as such the findings of this study will be beneficial to the policymakers of developing economies like India so that they may formulate effective guidelines to promote the culture of CE and Industry 4.0. In developing countries, organizations are still reluctant to adopt sustainability and technological innovations. Policymakers should therefore formulate guidelines for honing the skills of their workforce to adopt new changes in the era of CE and Industry 4.0. The government should also think about incentivizing adoption of emerging technologies in operations. By adopting concepts of CE and Industry 4.0, organizations would be more sustainable and competitive in global markets.

6. Conclusion and future scope

In the present business environment of Industry 4.0 and CE, digitization of processes has become a critical success factor to remain competitive. To ensure sustainability of operations, digitization of processes requires linkage of Industry 4.0 technologies with CE dimensions. Organizations are facing many barriers that hinder exploiting the benefits of CE and Industry 4.0 and the biggest challenge for existing production systems is how to adopt these technological changes in an effective and integrated manner (Singh et al., 2019, Bhandari et al., 2019). Organizations need to adopt a holistic approach for handling these sustainability barriers in the present business environment.

In this study, nine-criteria of sustainability and fifteen barriers for sustainable operations are considered. An integrated approach comprising of AHP and ELECTRE has been used for ranking of sustainability criteria and different barriers. Resource circularity, increasing profits from green products, process designs that enable high efficiency are major sustainability criterion. It has been observed that major barriers in the way of sustainable operations of supply chains are a lack of skilled workforce, ineffective performance framework and short-term goals of an organization.

Most of the existing workforce is not familiar with the emerging technologies of Industry 4.0. Due to a lack of awareness and knowledge, organizations are not able to use them for meeting objectives of the CE. The short-term goals of management is another considerable barrier; it diverts managements' attention from integrating Industry 4.0 based technologies with sustainability criteria in performance evaluation. Organizations hesitate to make large monetary investments in industry 4.0 technologies and traditional performance frameworks are not relevant in the current business environment. Organizations should design a performance framework that considers the current business environment of Industry 4.0 and CE. Risk of misinvestment, insufficient legislation and control, and employees' resistance to change within the existing production system also work as barriers against the implementation of sustainability. Ranta et al. (2018) have observed that organizations have a fear factor regarding monetary investments in these technologies.

There are many emerging sustainable practices, such as life cycle assessment, design for disassembly/recycling, refurbishment/remanufacturing, design for modularity, bio-based materials, product labelling, energy management, community involvement and socially responsible consumption. To overcome barriers and achieve the objective of sustainable supply chain operations, organizations need to explore sustainable practices as per specific requirement. To ensure that these practices have maximum effect, judicious use of Industry

4.0 technologies should be thoroughly explored. As a future scope of the study, a framework for strategies to overcome barriers can be also proposed. This framework can be used to analyze impact of these strategies on the performance of an organization by using structural equation modelling or case studies.

Limitations: The analysis of this research is based on the opinion of five experts in the manufacturing industry in India. Therefore, findings of the study cannot be generalized because observations may differ from one industry to another. There may be minor variations in results due to changes in the experts' opinions. Additionally, the authors have taken the crisp value for analysis, which may not be able to capture vagueness in the decision making of the experts. The fuzzy approach may be applied in future research to validate the findings. For a generalization of the findings in the future, empirical studies may be also carried out across manufacturing organizations of different sectors.

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Appendix: Calculation steps in ELECTRE

(a) The barriers of sustainable operations of supply chains are rated with respect to the various criteria (sustainability parameters of CE) on a 5-point rating scale using equation (A1):

$$X = \left[x_{ij} \right] \quad \text{(A1)}$$

(b) The decision matrix prepared in step (a) is normalized using Equation (A2):

$$R = \left[r_{ij} \right] \quad \text{(A2)}$$

$$Where \;\; r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}};$$

$i = 1, 2, \ldots n$ represents the specific criteria; and $j = 1, 2, 3, \ldots, m$ represents the specific barriers.

(c) Weighted normalized matrix is prepared using Equation (A3).

$$V = [v_{ij}] \quad \text{(A3)}$$

$$Where \;\; v_{ij} = r_{ij} \times w_i$$

(d) The concordance and discordance sets of criteria are found for each barrier using the threshold as mentioned in Equations (A4) and (A5)

$$C_{kl} = \left\{ I \mid v_{ik} \geq v_{il} \right\} \quad \text{(A4)}$$

$$D_{kl} = \left\{ I \mid v_{ik} < v_{il} \right\} = I - C_{kl} \quad \text{(A5)}$$

Where C_{kl} is the set of concordance criteria and D_{kl} is the set of discordance criteria.

(e) The concordance matrix is prepared using Equation (A6):

$$C = \left[c_{kl} \right], and$$

$$c_{kl} = \sum_{i \in C_{kl}} w_i / \sum_{i=1}^{n} w_i; \qquad where \;\; 0 \leq c_{kl} \leq 1 \quad \text{(A6)}$$

Here, c_{kl} is a summation of the weights of concordance criteria for which the k^{th} barrier is preferred over the l^{th} barrier.

(f) The discordance matrix prepared using Equation (A7):

$$D = [d_{kl}], and$$
$$d_{kl} = \frac{\max_{i \in D_{kl}} | v_{ik} - v_{il} |}{\max_{i \in I} | v_{ik} - v_{il} |}; \quad where \;\; 0 \le d_{kl} \le 1 \qquad (A7)$$

Here, the numerator shows the maximum difference distance between the weighted normalized elements of k^{th} and l^{th} barriers considering only those criteria for which the k^{th} barrier is inferior to the l^{th} barrier. Denominator shows the maximum difference distance between k^{th} and l^{th} barriers for all the criteria.

(g) The average value of c_{kl} is found using Equation (A8)

$$\bar{c} = \sum_{k=1, k \ne l}^{m} \sum_{l=1, l \ne k}^{m} c_{kl} / m(m-1) \qquad (A8)$$

(h) A Boolean Matrix E is prepared based on the values of c_{kl} and $\bar{c}$ as shown in Equation (A9):

$$\begin{aligned} e_{kl} &= 1; \;\; for\, c_{kl} \ge \bar{c} \\ &\;\;\; 0; \;\; for\, c_{kl} < \bar{c} \end{aligned} \qquad (A9)$$

(i) The average value of d_{kl} is found using Equation (A10)

$$\bar{d} = \sum_{k=1, k \ne l}^{m} \sum_{l=1, l \ne k}^{m} d_{kl} / m(m-1) \qquad (A10)$$

(j) A Boolean Matrix F is calculated based on the values of d_{kl} and $\bar{d}$ as shown in Equation (A11):

$$\begin{aligned} f_{kl} &= 0; \;\; for\, d_{kl} \ge \bar{d} \\ &\;\;\; 1; \;\; for\, d_{kl} < \bar{d} \end{aligned} \qquad (A11)$$

(k) The elements of the matrix E with the corresponding elements of matrix F are multiplied to get the aggregate dominance matrix G using Equation (A12):

$$\begin{aligned} &G = [g_{kl}] \\ &where \;\; g_{kl} = e_{kl} \times f_{kl} \end{aligned} \qquad (A12)$$

Based on the final dominance matrix, we can find the dominance of one alternative over another and we can map the outranking relationship of the substitutes with respect to the other dominant substitutes.