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Industry 4.0 as an enabler of sustainability diffusion in supply chain: an analysis of influential strength of drivers in an emerging economy

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Industry 4.0 as an enabler of sustainability diffusion in supply chain: an analysis of influential strength of drivers in an emerging economy

***Abstract**:* Industry 4.0 (I4.0) and sustainability are recent buzzwords in manufacturing environments. However, the connection between these two concepts is less explored in the literature. In the current business context, the future generation of manufacturing systems is greatly influenced by the rapid advancement of information technology. Therefore, this study aims to examine the drivers of I4.0 to diffuse sustainability in Supply Chains (SCs). This research identifies the most relevant drivers through the literature and discusses them with area experts. Afterwards, an empirical analysis is conducted to validate the key drivers. Finally, the Grey based DEMATEL method is employed to examine the influential strength of the identified drivers and to build an interrelationship diagram. 'Government supportive policies' and 'Collaboration and transparency among supply chain members' were reported as highly significant drivers of I4.0. This study is an initial effort that investigates the key drivers of I4.0 to achieve high triple bottom line (ecological-economic-social) gains in SCs by taking an example from an emerging economy, i.e. India. This study may help managers, practitioners and policy makers interested in I4.0 applications to diffuse sustainability in SCs.

Keywords: Drivers, Industry 4.0, Supply Chain Management, Emerging Economies, Sustainability.

1. Introduction

The German federal government introduced, in 2011, the term Industry 4.0 (I4.0) as an element of the country's high technology plan (Hermann et al., 2016; Buer et al., 2018; Xu et al., 2018) to enhance its industrial capability through digitally controlled manufacturing. I4.0 is a competent approach to influence whole business processes (Hofmann and Rüsch, 2017). It helps in managing complex systems efficiently by making them real time sensitive (Müller et al., 2017; Vernadat et al., 2018; Dolgui et al., 2018) and integrating the application of Internet of Things (IoT) and information technology services for an intelligent environment (Duarte and Cruz-Machado, 2017; Kusiak, 2018).

I4.0 has been materialised globally and popularly adopted by German firms such as Volkswagen, Daimler and BMW, etc. Recently, the Indian and Chinese Governments have also introduced the "Make in India" and "Made in China 2025" strategies (Li, 2018) respectively. These strategies focus on improving manufacturing efficiency through process digitalisation. Similar initiatives have also been undertaken by the US, French, UK, Japanese and Singaporean Governments (Bag et al., 2018; Luthra and Mangla, 2018a). I4.0 is distinguished in terms of higher adaptability, resource usage, economics, integrating customers and business partners in a SC context (Fallahpour et al., 2017c). I4.0 visualises factories and SCs in such a manner that products and equipment are all interlinked through the internet, communicate with each other and exchange/collect/analyse data (Sung, 2018) and processes in the system through Cyber-Physical Systems (CPS) (Branke et al., 2016). CPS can be understood as transformative technologies for interconnecting systems between its physical devices and computational assets (Lee et al., 2015; Leitão et al., 2016).

However, it is critical to note that the adoption of I4.0 in the manufacturing sector is easier in developed economies as compared to developing economies (Fettermann et al., 2018). Table 1 presents a list of the top 20 countries in regards to their contribution to the world's manufacturing sector.

Table 1: Contribution of the top 20 countries to the world's manufacturing sector

Rank	Country	Total GDP* (Global ranking)	MFG Contrib. (Billion $)	MFG Contrib. (%)	EMP	Digital readiness	Type of Economy
1	China	11938 (2)	4715.35	39.50%	23.70%	13.64 (accelerate)	Developing
2	United States	19362 (1)	3659.44	18.90%	17.50%	20.1 (amplify)	Developed
3	Japan	4884.5 (3)	1450.7	29.70%	26.80%	17.33 (amplify)	Developed
4	Germany	3651.9 (4)	1099.22	30.10%	27.80%	17.68 (amplify)	Developed
5	France	2439 (7)	704.87	28.90%	20.70%	16.98 (amplify)	Developed
6	South Korea	1529.7 (11)	593.52	38.80%	25.10%	14.5 (accelerate)	Developed
7	United Kingdom	2574.8 (5)	499.51	19.40%	18.70%	17.84 (amplify)	Developed
8	India	2565.1 (6)	487.37	19.00%	24.20%	10.54 (accelerate)	Developing
9	Russia	1469.3 (12)	476.05	32.40%	27.20%	13.33 (accelerate)	Developed
10	Italy	1921.1 (9)	461.06	24.00%	27.20%	14.11 (accelerate)	Developed
11	Canada	1640.4 (10)	460.95	28.10%	21.40%	17.11 (amplify)	Developed
12	Brazil	2080.9 (8)	436.99	21.00%	21.60%	11.8 (accelerate)	Developing
13	Indonesia	1010.9 (16)	407.39	40.30%	22.20%	11.73 (accelerate)	Developing
14	Australia	1390.2 (13)	362.84	26.10%	21.80%	17.34 (amplify)	Developed
15	Mexico	1142.5 (15)	361.03	31.60%	25.10%	13.11 (accelerate)	Developing
16	Spain	1307.2 (14)	303.27	23.20%	19.70%	14.91 (amplify)	Developed
17	Saudi Arabia	678.5 (20)	299.9	44.20%	22.70%	13.35 (accelerate)	Developed

18	Turkey	841.2 (17)	267.5	31.80%	27.80%	12.58 (accelerate)	Developing
19	Taiwan	571.5 (22)	205.74	36.00%	23.60%	10.95 (accelerate)	Developed
20	Poland	510 (24)	205.02	40.20%	30.20%	13.89 (accelerate)	Developed

*Billions of dollars, EMP= Employment in manufacturing sector

(Sources: CISCO, World Bank, Industrial Development Report 2018)

From the list of countries presented in Table 1, 14 are developed and 6 are developing economies. China has the largest manufacturing contribution (39.5%) to the GDP. Several developed countries across the globe are shifting towards offshore outsourcing (Yadav et. al 2018); and for this purpose, developing economies have turned out to be the most optimum choice. Developing economies commonly provide cheap labour, low cost of facility location, and raw materials. Similarly, digital readiness is an important criterion in the manufacturing sector. The country's digital readiness score ranges on a scale from 0 to 25, including technology infrastructure, technology adoption, human capital, basic needs, ease of doing business, government investment and start-ups linking digitisation (CISCO). Most of emerging nations such as China, India and Brazil, etc. are not the strongest players in digital readiness as compared to well-established industrialised nations such as United States of America (20.1), United Kingdom (17.84) and Germany (17.68).

Certainly, I4.0 and sustainability have a strong link (Müller et al., 2018). From a managerial perspective, it is irrational to talk about innovation and industry at the cost of sustainable business development. I4.0 forms a sustainability viewpoint, in terms of improving economic-ecological-social efficiency of processes, carbon emission control, reduction of waste and saving of resources and improved life-style for customers or future generations (Fallahpour et al., 2017a). I4.0 is a combination of digitisation and intelligence of business operations and processes and has a huge scope of applicability in different areas (Lin et al., 2017). Therefore, industrial sectors cannot ignore the influencing impact of I4.0 on SCs and their sustainability (Quezada et al., 2017; Liao et al., 2017; Fallahpou et al., 2017b; Grant Thornton India Report, 2017). In doing so, production managers should integrate I4.0 approaches and industrial developments to accomplish their environmental, economic and social sustainability objectives (de Sousa Jabbour et al., 2018). In addition to this, industries should effectively practice techniques and methods pertaining to I4.0 to shape their processes and operations for sustainable development in a SC context (Tseng et al., 2018). However, the adoption of I4.0 technologies is still in an initial stage, especially in developing nations such as India (Luthra and Mangla, 2018a). Industries know that I4.0 has its own challenges and impacts in regards to its implementation (Kamble et al., 2018), but that at the same time it has potential to contribute to ecological-economic-social sustainability (Fallahpou et al., 2016; Mangla et al., 2018a; Luthra and Mangla, 2018a; Govindan et al., 2018). The research of Stock et al. (2018) reported that there is still a lack of research on which drives I4.0 towards sustainability. This is justifying the need to distinguish and examine key drivers to integrating the I4.0 approach into SCs for achieving truly sustainable SCs. To address this, the present work identifies the following research questions:

RQ1: What are the key drivers and their influential strength of I4.0 to diffuse sustainability in SCs?

To answer the above-mentioned question, the study has the following objectives:

i. To investigate key drivers of I4.0 to diffuse sustainability in SCs from the perspective of an emerging economy;
ii. To analyse the influential strength (cause-effect interrelationship) of listed key drivers.

In this work, the key drivers of I4.0 to diffuse sustainability in SC are identified and validated through literature and experts' opinions. The DEMATEL technique allows extracting causal interactions along with the definition of the strength of interactions between the considered drivers (Garg et al., 2014). DEMATEL is helpful in examining the interactions among drivers; however, it has limited applicability while describing the uncertain relationships. Globally, business organisations are slowly moving towards the implementation of I4.0 technologies to avoid perishing in this volatile, uncertain, complex and ambiguous environment (Bag et al., 2018). In this sense, Grey set theory is a useful option, which allows integrating uncertainty and vagueness in the adoption of I4.0. Considering this, the study proposes the utilisation of a Grey-DEMATEL methodology for examining the causal relations of the key drivers (Xia et al., 2015).

This work is divided into six sections. The relevant literature is given in Section 2. Section 3 is related to the application of the solution methodology. Analysis is presented in Section 4. The findings of the study are provided in Section 5. Finally, the last section of the paper presents the concluding remarks along with the unique contributions of study and future research directions.

2. Literature Review

This section presents a literature review on Industry 4.0 and Sustainability in SCs, and identifies the key drivers. Research gaps are also identified.

2.1 Industry 4.0 and Sustainability in SC

In the rapid developments of production processes and business automation, I4.0 has been termed as the Fourth Industrial Revolution (Piccarozzi et al., 2018). I4.0 has been integrated in different forms, i.e. horizontally across value networks and vertically across production systems (Brettel et al., 2011). I4.0 is primarily driven by smart technologies supported by internet and internet-based technologies like cloud computing, CPS, big data analytics, robotics, visual graphics, and smart networks, distributed manufacturing, etc. This provides means to connect equipment, networks, and people wherever required (Fatorachian and Kazemi, 2018). I4.0 objectives are to create a network of intelligent products, manufacturing processes and machines. From a managerial viewpoint, organisations need to meet the requirements of rapid product development and design as well as speedy and flexible production in business environments (Brettel et al., 2011). I4.0 is a business strategy, which has huge implications for industries. I4.0 has a great potential to influence considerably SC networks, business processes and models (Duarte and Cruz-Machado, 2017). There are four essential components for developing the sustainability of industrial SCs through I4.0. These components include using advanced information technologies in manufacturing systems, high performance manufacturing, finding new raw materials and sustainable manufacturing. Additionally, industries can benefit from I4.0 technologies in terms of improving manufacturing efficiency, making communities healthier, saving resources, high interconnectivity, and ultimately contributing to a truly sustainable development of SCs. Managers and practitioners must design the implementation of I4.0 technologies considering key drivers that have the potential to achieve high ecological-economic-social gains (sustainability) in SCs (Bag et al., 2018). Now, business organisations also have accepted the importance of digital transformation for sustainability development of SCs.

Thus, it is important to identify the drivers to I4.0 for industries to understand its real impact on SCs sustainability, especially in the case of developing countries, where the concept is relatively new (Mangla et al., 2018a; Kumar et al., 2018; Luthra and Mangla, 2018a).

2.2 Key Drivers to I4.0 to Diffuse SC Sustainability

A driver can be defined as “a resource, process or condition” that is necessary for the successful implementation and growth of a business (Govender and Pretorius, 2015). In emerging economies, I4.0 implementation to accomplish sustainability in SCs is in an initial stage. Thus, the key drivers must be known and analysed for an effective implementation of I4.0 for sustainable SCs. In order to identify the drivers, the following keywords, i.e. Enablers/Drivers/Success Factors and Industry 4.0/Smart manufacturing/Cyber-physical systems/Smart production and Sustainability in supply chains, were searched in the existing literature. For this, Google Scholar and Google search engines were used. This further helped in linking various databases like Science Direct; ISI WoS; Emerald; Scopus; Taylor & Francis; DOAJ; EBSCO, Wiley and Inderscience. In the initial stage, 297 articles were listed from different journals and published papers in conference proceedings. After that, a screening process was conducted to select the relevant papers. The criteria for screening were: 1) the paper must be written in English language; 2) the paper must have gone through a peer-review process, 3) the paper must be related to I4.0 and supply chain and sustainability (ecological-economic-social). In this process, the authors referred to papers from relevant renowned journals such as "International Journal of Production Economics"; "International Journal of Production Research"; "Production Planning & Control"; "Journal of Cleaner Production"; "Technological Forecasting and Social Change"; "Computers & Industrial Engineering"; "Process Safety and Environmental Protection"; "Benchmarking: An International Journal"; "Resources, Conservation and Recycling" and "Sustainability". After a final screening, only 44 were kept. Further, some reports published by some reputed consultancy groups, foundations and governments were also considered due to the emerging nature of the subject matter in the context of developing countries. In this way, nine key drivers to I4.0 to diffuse sustainability in SC were identified from literature. The identified drivers were validated through discussions with experts from India; further details are provided in Section 4.1. A brief description of the identified drivers is provided in the following sub-sections.

2.2.1 Collaboration and transparency among supply chain members

Businesses need to build upon strong coordination and collaboration among SC members. Therefore, manufacturing organisations must ensure collaboration among various stakeholders to achieve sustainability in the SC (Liou et al., 2016). This driver is related to how I4.0 may help to create a long-term sustainable relationship with different members of the SC (Pfohl et al., 2017). Various studies have elaborated on the significance of coordination and collaboration for integrating I4.0 with SC to augment sustainability in operations (Pfohl et al., 2017; Luthra and Mangla, 2018a; Müller et al., 2018).

2.2.2 Management support and effective governance

The support from top management and their leadership style of taking initiatives drives the I4.0 adoption (Savtschenko et al., 2017; Bag et al., 2018). In addition, governance structure is crucial in deciding the plan of action in integrating I4.0 driven sustainable initiatives in an organisation. A proactive approach of top management and effective follow up of initiatives will help organisations to integrate I4.0 technologies with sustainability in their SCs (de Sousa Jabbour et al., 2018).

2.2.3 Development of infrastructure and Information Technology (IT) based facilities

The implementation of I4.0 is a typical and time-consuming process; the concepts should be shaped to fit the industry and its priorities. Rather than just investing in the latest equipment, the focus should be on improving processes and operational efficiency. Emerging academic research relates to how the principles, practices, and enabling technologies of I4.0 unlock the potentials of sustainable SCs (Leitão et al., 2016; Pfohl et al., 2017). This driver is all importance of infrastructure and IT based facilities such as advanced machinery and equipment, CPS, IoT and cloud computing in upgrading the systems to diffuse sustainability in the SC (de Sousa Jabbour et al., 2018). IoT will play an imperative role in completing I4.0 in the Indian market. In line with this, it is predicted that India will capture more than 20% share in global IoT market by the year 2025 (IBEF, 2016). In this way, huge infrastructure, IT based facilities and technologies are considered as key drivers for an effective implementation of I4.0 technologies.

2.2.4 Competitiveness

To survive in today's competitive business environment, it is important for organisations to update their supply system with advance technologies. This technological advancement will help organisations to not only survive in the market, but also cope with competition. Therefore, I4.0 initiatives are crucial in building a brand image and consequently improve competitive gains. In this sense, managers need to manage I4.0 related issues to drive sustainability in SCs, while building a good name in the market and improving their competitiveness (Müller et al., 2017; Wolf, 2017).

2.2.5 Improved information sharing system and resource development

Improved information sharing systems and resources development are important in terms of coordinating the efforts of various members of the SC and diffusing advanced technologies during I4.0 adoption (Wan et al., 2016; Tavana et al., 2017). Advanced technologies such as cloud computing and other modern communication platforms help in the planning and utilisation of shared resources as well as gaining better control over processes and obtaining better performances (Moeuf et al., 2018). Nevertheless, most industries, especially those of developing nations like India, are not technologically efficient. Additionally, proper awareness of I4.0 influences an organisation's ability to adopt Industry 4.0 to achieve ecological-economic-social gains throughout its SC (Pfohl et al., 2017).

2.2.6 Reduction in waste and improved cost efficiency

I4.0 would result in the reduction of the generation of waste and improved cost efficiency through a SC (Rüßmann et al., 2015; Bag et al., 2018). It is stated that initially, I4.0 technologies may increase the overall organisation's cost during its adoption. However, the overall performance of the business in terms of economic-gains will be improved in the long run (Hermann et al., 2016).

2.2.7 Workforce knowledge and expertise in managing resources

The implementation of I4.0 requires a workforce to acquire new skills (Schuster et al., 2016; Fettermann et al., 2018). Training and development programs for the workforce are useful for implementing I4.0 in the shop floor (Lin et al., 2017; de Sousa Jabbour et al., 2018). Workforce knowledge and expertise in managing resources will contribute to provide an obvious linkage between I4.0 and SC sustainability (Lin et al., 2017; de Sousa Jabbour et al., 2018). Liboni et al. (2019) reported that the lack of skilled staff can inhibit radical changes towards I4.0 across entire SCs, as human issues can affect sustainability in SCs. Thus, for enhancing the sustainability of SCs operations through I4.0, organisations need to ensure required skills set among their employees.

2.2.8 Government supportive policies

Sustainability has become a core value to maintain for manufacturing systems. I4.0 can help in making SCs more effective, efficient and responsive. However, during the adoption of I4.0, and to accomplish sustainability in SC, strong government support and policies are required (Kagermann, 2015; Hermann et al., 2016; Bag et al., 2018). Bonilla et al. (2018) stated that governmental policies play a key role in supporting business organisations and providing the necessary support in the implementation of I4.0 technologies.

2.2.9 Adoption of innovative business models

Industries need to upgrade themselves in terms of process innovations and usage of innovative models to meet the globalised demand (Stock and Seliger, 2016). Sophisticated technological developments and innovative business models should be employed to develop products and processes to drive the sustainability of material and goods throughout their life cycle (Branke et al., 2016; Agostini and Filippini, 2019).

2.3 Research Gaps and Problem Definition

Currently, I4.0 is well introduced in the manufacturing industry of developed nations. However, in the recent past, investment and plans to adopt I4.0 are happening in developing nations as well. For instance, China is leading the initiative "Made in China 2025"; the proposal is to encourage every factory in China to be a smart factory by 2025. In line with this, the Indian Government has also introduced the "Make in India", which focuses on improving manufacturing performance through digitalisation. At the same time, industries of developing countries are facing several challenges in adopting the term I4.0 and understanding its impacts on the sustainability of their SCs (Schmidt et al., 2015; Tseng et al., 2018). Therefore, the identification of the key implementation drivers can help industries in the effective adoption of I4 for sustainable SCs (Hermann et al., 2016).

I4.0 outlines a visualisation of the future of SCs (de Sousa Jabbour et al., 2018), but in the literature very limited discussion is available at both micro and macro level perspectives of I4.0 in businesses. This means that substantial research efforts are needed to understand I4.0 and adopt I4.0 implementation drivers for developing sustainability in SCs (Schmidt et al., 2015; Glas and Kleemann, 2016), which is being pursued in this work. In line with this, the implementation of I4.0 for sustainability in SCs is a difficult task. To make it happen, managers should focus on both the human and technology aspects (Glock et al., 2017). In addition, a significant level of understanding is required to understand the causal relations among drivers to I4.0 to improve ecological-economic-social gains in SCs (Ivanov, 2018). To this support, potential drivers need to be suggested for enhancing the success rate of I4.0 based sustainability initiatives in businesses (Ivanov, 2018; Kamble et al., 2018). In order to deal with these gaps in research, this work identifies the drivers of I4.0 to diffuse sustainability in SCs with the support of the literature and experts' inputs. These drivers were then analysed to determine their causal relations using the Grey-DEMATEL technique.

3. Solution Methodology

In order to achieve the objectives of the study, the research methodology framework presented in Figure 1 was followed.

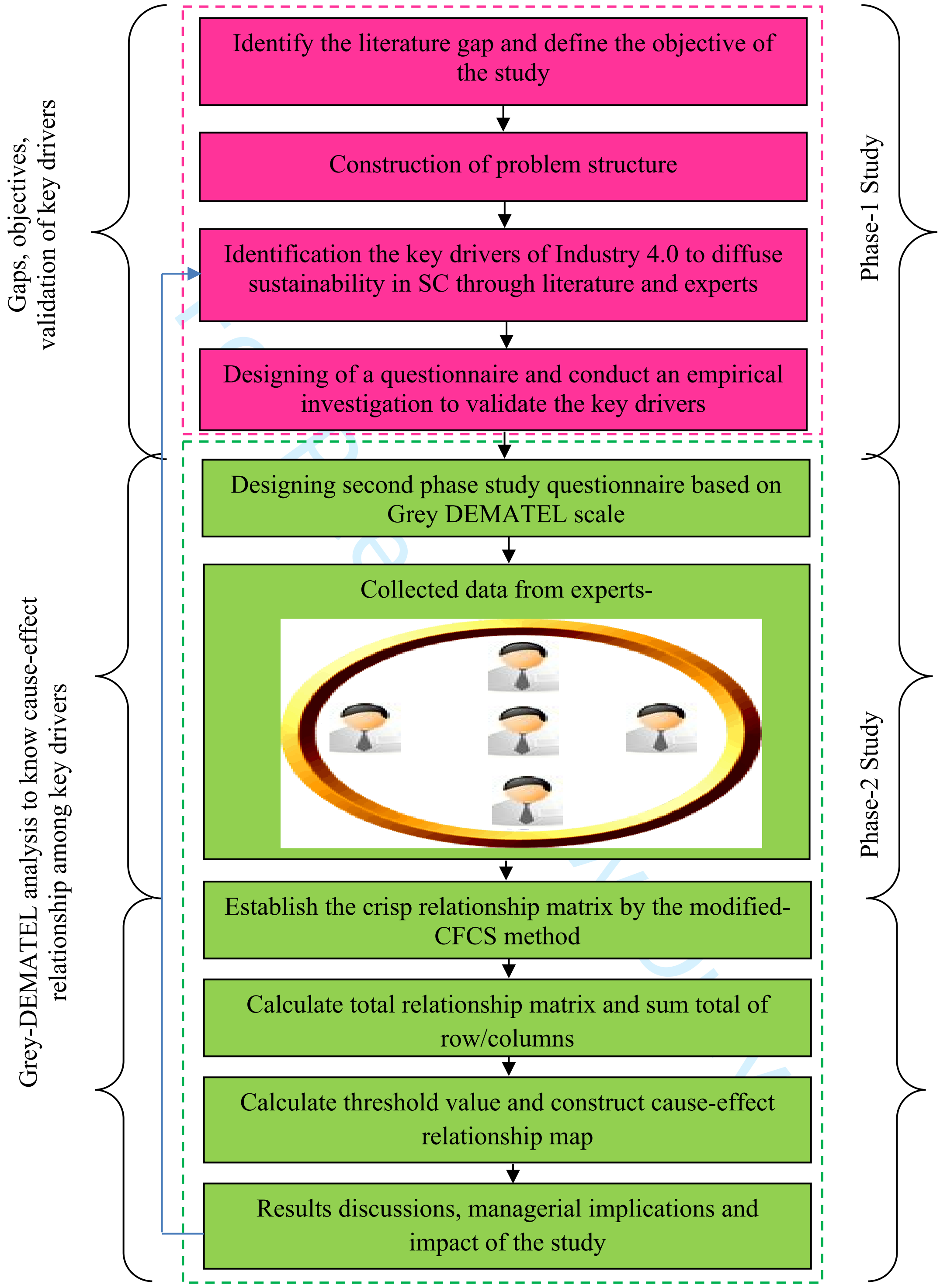

Figure 1. Methodology framework followed to conduct the study

To carry out the analysis part for the present work, Grey-DEMATEL was employed as a solution methodology. By applying the DEMATEL approach, the interrelation between the drivers can be scrutinized and presented in the form of a causal relationship (network) diagram.

Other methods, like the AHP technique is not able to map the interdependence and the cause-effect relationship between the factors (Mangla et al., 2018b). On the other hand, the Analytic Network Process (ANP) examines criteria and alternatives having very strong interactions, and may also have a high effect in decision making. However, the ANP approach is also not preferred by decision makers due to its complex use and understanding. On the contrary, DEMATEL has gained a significant acknowledgment, as it assists in evaluating the causal interactions among decision criteria (Bai and Srakis, 2013).

In practical situations, decision making may involve inconsistency due to human bias and unclear information. Consequently, the DEMATEL technique is also not effective in unclear surroundings (Xia et al., 2015). To overcome this drawback, fuzzy concepts can be integrated with the DEMATEL; however, fuzzy based DEMATEL also fails in mapping a membership function (Luthra et al., 2017). As a result, this work attempts to integrate Grey set theory with DEMATEL to evaluate the drivers. Prof. Deng in 1982 proposed the theoretical model of Grey set theory (Ju-Long, 1982). It has been suggested that Grey theory can easily be integrated with other decision-making techniques to make more sensible decisions under human involvement (Zavadskas et al., 2016; Bouzon et al. 2018).

The application of the Grey-DEMATEL methodology in decision making is shown in Table 2.

Table 2: Applications of Grey-DEMATEL technique reported in the literature

S. No.	Sources	Description
1	Tain et al. (2019)	Selected the take-back pattern of vehicle reverse logistics
2	Luthra et al. (2018)	Modelled the critical success factors for sustainable SCs
3	Asad et al. (2016)	Modelled the flexibility capabilities of IT-driven value chain
4	Shao et al. (2016)	Analysed the barriers taking aspects of ecologically driven products and consumers: practitioners' contexts
5	Govindan et al. (2016)	Evaluated the third-party logistics.
6	Su et al. (2016)	Improved the performance of sustainability in SC
7	Xia et al. (2015)	Evaluated the barriers for remanufacturing of truck-engine in a value chain
8	Rajesh and Ravi (2015)	Modelled the risk mitigation enablers in an e-SC
9	Bai and Sarkis (2013)	Evaluated the business process management success factors
10	Fu et al. (2012)	Examined the green supplier evaluation problem

11	Bouzon et al. (2018)	Evaluation of reverse logistics adoption

The steps undertaken while applying the Grey–DEMATEL technique are explained as follows.

Step 1: Develop the initial relationship matrix (*R*).

Step 2: Estimate the Grey matrices ($\otimes A_{xy}^{l}$) as per Eq. (1) (Rajesh and Ravi, 2015) i.e.

$$\otimes A_{xy}^{l} = \left(\underline{\otimes} A_{xy}^{l}, \overline{\otimes} A_{xy}^{l}\right) \quad (1)$$

Where 1≤ l ≤ n; 1 ≤ x ≤ c; 1 ≤ y ≤ c.

Step 3: Establish the average Grey matrix ($\otimes \check{A}_{xy}$)using Eq.(2).

$$\otimes \check{A}_{xy} = \left(\sum_{l} \frac{\underline{\otimes} A_{xy}^{l}}{n}, \sum_{l} \frac{\overline{\otimes} A_{xy}^{l}}{n}\right) \quad (2)$$

Step 4: Establish the crisp relationship matrix (*B*) by the modified-CFCS method (Xia et al., 2015) (For more details please see Appendix A).

Step 5: Establish the normalised direct-relation matrix (*N*) through Eqs. (3) and (4), as given below.

$$L = \frac{1}{\max_{1 \le x \le c} \sum_{y}^{c} a_{xy}} \quad (3)$$

$$N = L * R \quad (4)$$

Step 6: Determine the total relation matrix (*T*) by using Eq.5.

$$T = N(I - N)^{-1} \quad (5)$$

Where, '*I*' is the identity matrix.

Step 7: Determine the causal parameters by using Eqs. (6) and (7):

$$R = \left[\sum_{y=1}^{c} a_{xy}\right]_{c \times 1} \quad (6)$$

$$D = \left[\sum_{y=1}^{c} a_{xy}\right]_{1 \times c} \quad (7)$$

Step 8: Draw the causal diagram. If the driver has a positive value of (R-D), it indicates that the driver belongs to a cause group; otherwise it is an effect group driver.

4. Analysis

For data collection, an example of sustainability focused SC from India was considered. The problem was to drive the I4.0 application to help managers to establish the SC with a sustainability orientation. Indian manufacturing organisations are very focused in adopting the latest information communication technologies for improving their business performance and competitiveness at international level. The efforts of the Indian government in improving its manufacturing environment and business opportunities have also been recognised internationally. Further, India is expected to become the world's fifth largest manufacturer by 2020.

4.1 Phase 1 - Finalisation of the Drivers

This was an important process to check the importance of the identified drivers. Nine key drivers were itemised from the literature. To validate the identified drivers, an empirical process was followed. For this process, a structured questionnaire was prepared based on a 5 point Likert scale (5 = highly important to and 1 = highly unimportant). Experts from various manufacturing companies (Automotive component, High precision heavy machinery, Electronic components and Mobile phone manufacturing) as well as academic professionals from reputed institutes were contacted using personal connections. This work followed the convenience sampling method due to cost constraints. In total, 32 experts (2 General Managers, 5 Operations managers; 4 SC managers, 4 Production managers, 4 Industrial engineers, 2 Design engineers, 2 Environment engineers, 5 Senior professors of Operations Management and 4 Associate professor of Information Systems) from different companies as well as reputed academic institutes agreed to provide their feedback. The sample size was considered as satisfactory (Luthra and Mangla, 2018b). The selected experts were knowledgeable professionals, with a substantial working experience. As I4.0 is a very new concept, especially in emerging economies like India, and keeping this in mind, the research team contacted experts who knew well about I4.0 and its implications on sustainability in SC. Flexibility was provided to add any other driver/s, which were considered relevant for I4.0 to diffuse sustainability in SCs or to delete irrelevant drivers. All the experts agreed on the identified nine key drivers and no driver was added or deleted. In this way, the key drivers were identified as presented in Table 3.

Table 3: An empirical analysis of key drivers

Drivers	Mean	Standard deviation
Collaboration and transparency among supply chain members (D1)	3.65	0.970
Management support and effective governance (D2)	4.28	0.728
Development of infrastructure and IT based facilities (D3)	4.37	0.707
Competitiveness (D4)	3.91	0.856
Improved information sharing system and resource development (D5)	4.00	0.803
Reduction in waste and improved cost efficiency (D6)	3.78	0.941
Workforce knowledge and expertise in managing resources (D7)	4.46	0.671
Government supportive policies (D8)	4.09	1.027
Adoption of innovative business models (D9)	3.96	0.897

Table 3 indicates that the driver named 'Workforce knowledge and expertise in managing resources (D7)' obtains the highest mean score of 4.46, followed by 'Development of infrastructure and IT based facilities (D3)' with a score of 4.37. 'Management support and effective governance (D2)' and 'Government supportive policies (D8)' were in third and fourth positions with mean scores of 4.28 and 4.09 respectively.

4.2 Phase 2 - Analysis of Influential Strength of Drivers

After the validation of the identified key drivers, a second questionnaire was also designed for the second phase of the study. From the 32 experts previously selected (see Section 4.1), only 5 of them showed their interest in participating further in the present research. Group size can affect the results, but an over large decision-making group is also not recommended; it is suggested to be between 5 and 50 (Gumus, 2009). After following this process, data was collected from the 5 experts, which was considered an acceptable group size (Kumar et al., 2018; Kusi-Sarpong et al., 2019). Each expert was requested to evaluate the drivers as given in the scale presented in Table B1 (Appendix B).

After the formation of the expert panel, the proposed framework was applied in order to determine the causal relationship among drivers, Grey-DEMATEL was utilised. For uniformity of judgment, identical weightages were considered for all experts and the average Grey relation matrix $[\otimes \check{A}_{xy}]$ was calculated using Eq. (2). The crisp relation matrix (B) was built using the modified-CFCS method through Eqs. (A1) – (A5), this is shown in Table B2 (Appendix B). The N matrix was constructed using Eqs (3) - (4). The matrix T was obtained using Eq. (5), see Table B3 (Appendix B). Further, the values of R and D were calculated using Eqs. (6)- (7) as shown in Table 4).

Table 4: Cause and effect result for drivers

Drivers	R	C	R+C	Rank	R-C	Cause/Effect
D1	4.02	3.62	7.63	2	0.40	Cause
D2	3.86	3.44	7.30	3	0.42	Cause
D3	3.51	3.04	6.55	7	0.47	Cause
D4	1.63	3.28	4.91	9	-1.65	Effect
D5	3.74	3.55	7.29	4	0.19	Cause
D6	3.30	3.66	6.97	5	-0.36	Effect
D7	3.45	3.39	6.84	6	0.06	Cause
D8	4.31	3.58	7.89	1	0.73	Cause
D9	3.00	3.28	6.29	8	-0.28	Effect

The interrelationship diagram for key drivers is presented in Figure 2.

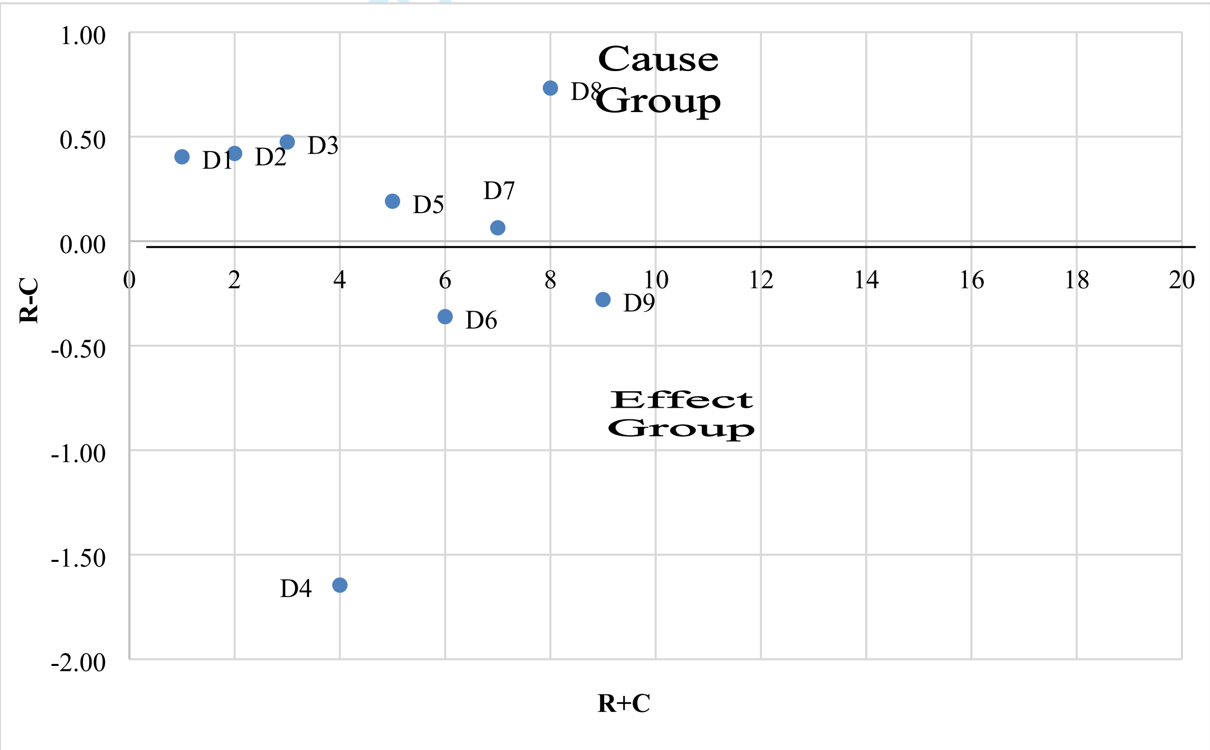

Figure 2. Cause and effect diagram for drivers

From Figure 2, it can be deduced that six drivers were in the cause group and three drivers were categorised in the effect group. A preference rating of drivers was also drawn, as shown in Figure 3. This helped mangers in making a comparative assessment of preference of considered drivers of I4.0 to diffuse sustainability in a SC context.

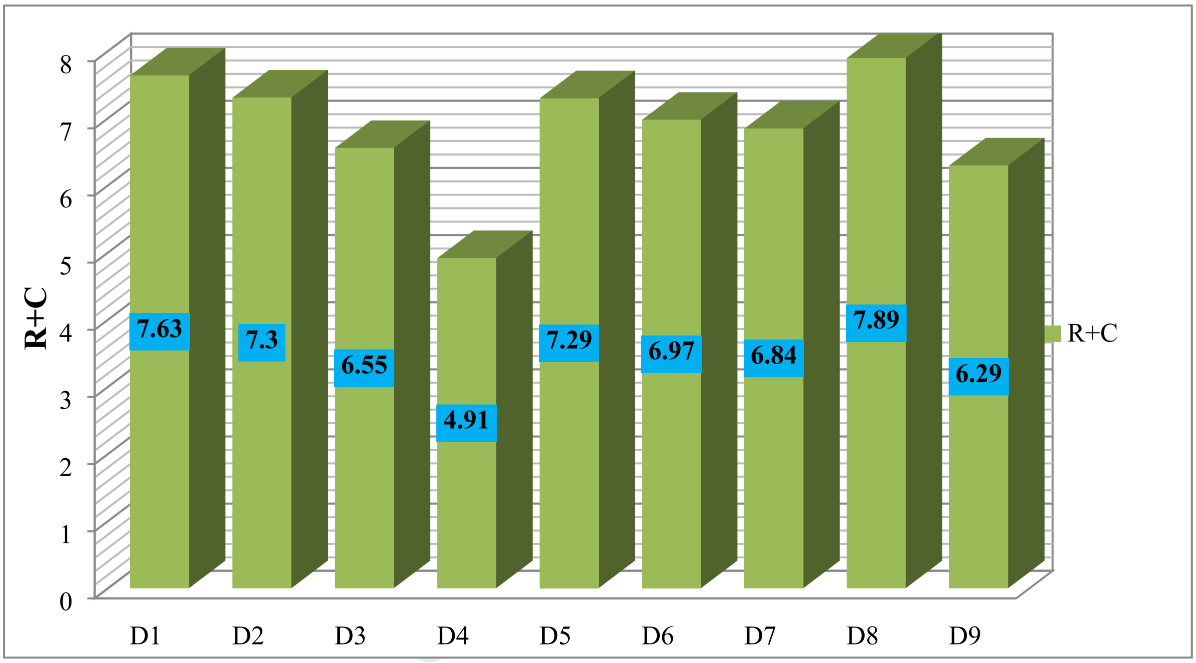

Figure 3. Preference ratings of drivers

Furthermore, the threshold value was calculated, which resulted to be 0.376. The threshold value revealed the snapshot of mutual interactions among the considered drivers. Based on this, an interaction matrix of drivers was also developed (see Table 5).

Table 5: Interaction matrix of drivers

Drivers	D1	D2	D3	D4	D5	D6	D7	D8	D9
D1		✓	✓	✓	✓	✓	✓	✓	✓
D2	✓		✓	✓	✓	✓	✓	✓	✓
D3	✓	✓		✓	✓	✓	✓	✓	✓
D4	✓		✓			✓	✓	✓	✓
D5	✓	✓		✓		✓	✓	✓	✓
D6	✓	✓	✓		✓				
D7	✓			✓	✓	✓		✓	✓
D8	✓	✓	✓	✓	✓	✓	✓		✓
D9	✓							✓	

Note - ✓ represents the presence of inter-relationship between the drivers

From Table 5, an impact interrelationship (network) diagram for the driver was also constructed as shown in Figure 4.

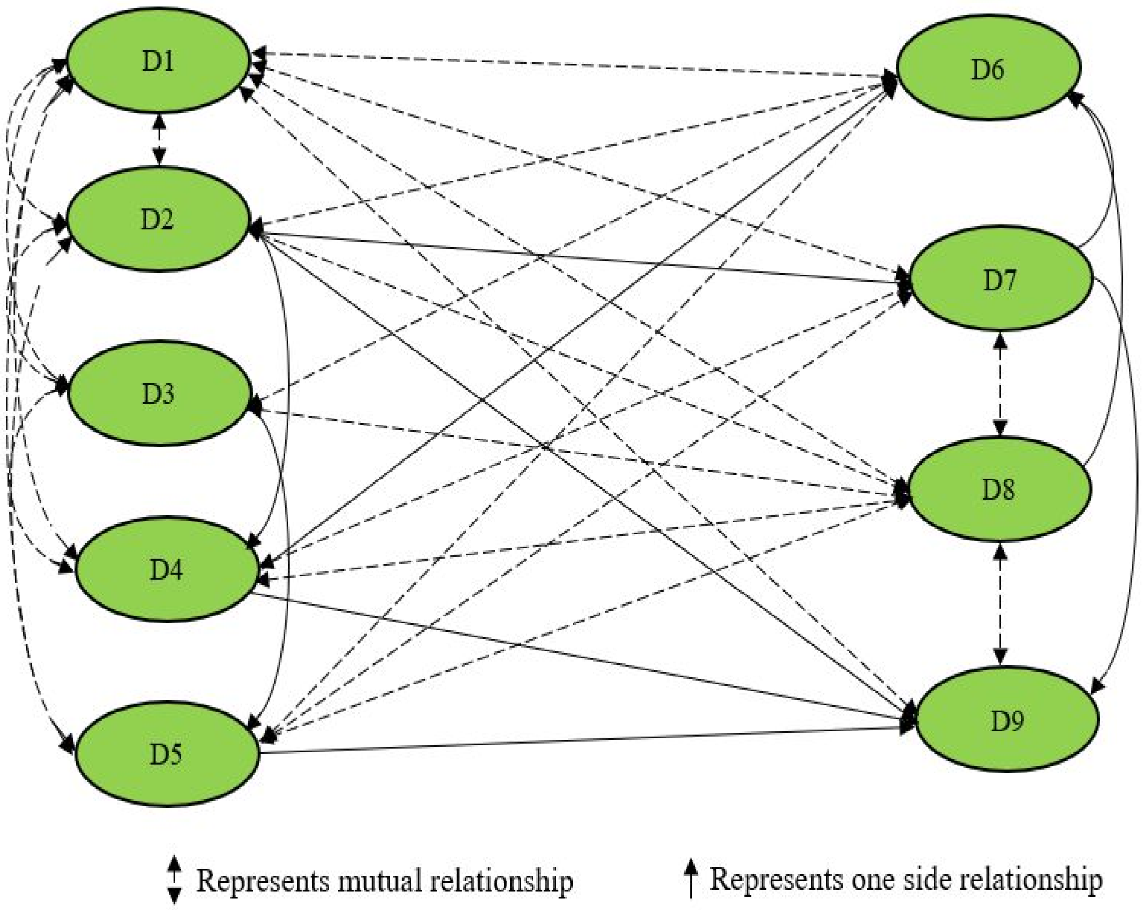

Figure 4. Interrelationships (network) diagram of the drivers

Figure 4 illustrates the interaction of drivers with each other. There were two types of interactions among drivers, which included mutual relationships and one-side relationships. In mutual relationships, both drivers influenced each other, whereas in one-side relationships, particular drivers influence other drivers. For instance, 'Collaboration and transparency among supply chain members (D1)' and 'Management support and effective governance (D2)' had mutual interactions. On the other hand, 'Management support and effective governance (D2)' influenced 'Competitiveness (D4)' to successfully implement I4.0 and achieve sustainability within a SC context. A proper understanding about mutual and one-side relationship helps managers in effectively managing the adoption of I4.0 to diffuse sustainability in SCs.

5. Discussion of Findings

Based upon R-C dataset values, six drivers namely 'Government supportive policies (D8)', 'Development of infrastructure and IT based facilities (D3)', 'Management support and effective governance (D2)', 'Collaboration and transparency among supply chain members

(D1)', 'Improved information sharing system and resource development (D5)' and 'Workforce knowledge and expertise in managing resources (D7)' were categorised as cause group drivers. Therefore, a highly focused approach is required for these cause group drivers.

The cause and effect diagram for the drivers is presented in Figure 2, which suggests that 'Government supportive policies (D8)' has the maximum influence on the other drivers. From Figure 4, this driver has a mutual relationship with all the other drivers, except with the driver 'Reduction in waste and improved cost efficiency (D6)' has a one-side relationship. It means that government supportive policies will play a significant and important role for adopting I4.0 to achieve sustainability (i.e. economic, social and environment) in SCs. The findings of the study are supported by previous studies in the literature, for instance, Kuo and Smith (2018) also suggested the importance of supportive government policies, indicating that the goal of sustainable industrial systems could not be possible without the support of the government. Similarly, the research of Sung (2018) suggested that government supportive policies are necessary to develop economic-ecological-social systems to flexibly respond to changes and operational systems to maximise the efficacy of initiatives.

The driver 'Development of infrastructure and IT based facilities (D3)' resulted in second position. After observing Figure 2 and Figure 4, this driver is in the cause group and has a mutual relationship with other drivers; expect the driver 'Improved information sharing system and resource development (D5)' which means that this reasonably affects other drivers. It indicates that Indian manufacturing companies need to invest heavily in CPSs for developing a sustainable manufacturing environment. Thus, a proper implementation of I4.0 in industry would help businesses to connect machines, people, networks and software, which would further help to diffuse sustainability (i.e. economic, social and environment) in their supply chain processes.

'Management support and effective governance (D2)' is in third position. I4.0 describes a vision of intelligently automated factories, which is impossible without management support and effective governance. This driver belongs to the cause group and has a mutual relationship with other drivers. The research of Piccarozzi et al. (2018) also suggested that I4.0 adoption requires substantial support from internal and external levels. Effective governance will help management in formulating effective strategies for a smooth transition towards I4.0, considering all economic, environmental and social issues for sustainability in SCs. For instance, the implementation of I4.0 would bring organisations economic benefits (cost effectiveness and proper utilization of resources, etc.), environmental benefits (waste reduction and reduced energy consumption, etc.) and social benefits (enhanced employee leanings, human and machine interface, etc.) (Herrmann et al., 2014; Ding et al., 2017) to achieve truly sustainable SCs.

The next cause group driver is ‘Collaboration and transparency among supply chain members (D1)’. This driver has a mutual relationship with several other drivers. SC structures are highly influenced by people and machines complexities within a system, hence more visible and transparent networks are required in such situations (Pfohl et al., 2017). In addition, collaboration among SC members will help in increasing the transparency as well as efficient decision-making in the system, which plays a significant role for an organisation to survive in the long-term and in the current competitive market. Next, ‘Improved information sharing system and resource development (D5)’ is important in supporting I4.0 to develop sustainability in SCs. Improved information sharing and resource sharing system would help in increasing reliability and interconnectivity for successful cyber-physical communication. SC partners should effectively improve information sharing system and resource development to implement I4.0 for bringing higher economic-ecological-social gains. I4.0 is not just to achieve operational efficiency and performance, but also deliver better value to customers by integrating it with a product lifecycle. The last driver in the cause group was ‘Workforce knowledge and expertise in managing resources (D7)’. Workforce knowledge and expertise in managing resources plays a significant role in adopting I4.0 technologies and improving manufacturing efficiency for sustainable business development in SCs.

Moreover, three drivers namely ‘Adoption of innovative business models (D9)’, ‘Reduction in waste and improved cost efficiency (D6)’ and ‘Competitiveness (D4)’ were categorised into the effect group drivers. This group of drivers was influenced by other drivers and played the important role for the industrial managers and practitioners in understanding which driver is influenced by other drivers. This will further help managers in framing their business strategy. The effect group drivers can be seen as desired objectives of I4.0 to diffuse sustainability in SCs. It is necessary to control cause group drivers to reach a high level of performances with effect group drivers. Müller et al. (2018) concluded that I4.0 practices result in innovative business models, which are ultimately going to help in deriving economic benefits as well as enhancing competitiveness. Furthermore, the research of Tortorella and Fetterman (2018) suggested that I4.0 technologies implementation could be one of the best strategies to improve product quality as well as making manufacturing processes more efficient.

5.1 Implications of the Study

This study suggests managers to understand the drivers that facilitate the adoption of I4.0 for diffusing sustainability in SCs. The implications of this work are given as follows:

i. This work helps managers to transform their businesses into smart factories by understanding the nexus of adopting I4.0 for sustainable business development, like process innovation, technological applicability, infrastructure development and economic-ecological-social benefits.

ii. This work helps managers in understanding causal interactions among I4.0 sustainability-oriented drivers. A clear understanding of these causal interactions among drivers of I4.0 will help industry managers and practitioners to understand their influence in diffusing sustainability throughout SCs. This would further assist manufacturing organisations to improve their ecological-economic efficiency as well as people welfare through I4.0. For instance, the driver '*Collaboration and transparency among supply chain member*s' is in the cause group and influences all the other drivers. Therefore, industry managers can undertake more initiatives to enhance their collaboration with their suppliers and formulate more effective plans to make processes more transparent.

iii. The analysis of this study shows that the driver *government supportive policies* is in the cause group and influences almost all the other drivers to adopt sustainability in SCs. This research informs management to have effective governance for transforming a manufacturing system into a smart factory, with improved performance and time management. Additionally, government support and policies are crucial in promoting I4.0 technologies for saving resources and developing a sustainable culture in manufacturing environments. Government can provide subsidies and tax rebates to support the manufacturing sector for developing their infrastructure and capabilities in I4.0 technologies for a sustainable planet.

iv. Globalisation has become an important factor in deciding the growth of the manufacturing sector. From a managerial context, exploring the global market needs and benchmarking the standards in upgrading the traditional business to a high interconnected smart factory is significant. For the development of infrastructure and IT based facilities, organisations need to benchmark their processes and related procedures to understand the different I4.0 technologies (CPS, IoT and Big data etc.) and its related drivers for accomplishing sustainability objectives in their SCs.

v. This is significant to engage various stakeholders and arrange training programmes for the workforce in the adoption of I4.0. In order to develop an effective I4.0 concept with sustainability orientation, managers need to engage various stakeholders (internal and external) in decision-making. The engagements should be complemented by training and development programmes among SC members and stakeholders. Managers should aim to improve the skills and expertise of workers and staff by launching educational programmes, seminars, training sessions, with an exclusive focus on I4.0 and its implications on sustainability.

vi. From an industrial context, the implementation of I4.0 requires higher initial financial investment. However, management should consider I4.0 adoption as a strategic decision to improve their cost efficiency, reduce consumption of resources, energy and develop healthy societies. I4.0 financing may be very challenging, when considering the uncertainty of its success. Thus, a logical planning is needed to support its implementation in the manufacturing environment. To manage this issue, for instance, industry can invite more public investments.

6. Concluding Remarks

This is an incredibly exciting time for manufacturing systems to leap their technological advancements for the digital transformation of their SCs. There are several factors that are driving this industrial transformation in manufacturing organisations. This study is a preliminary effort to contribute in the identification of key drivers of I4.0 to diffuse sustainability in SC. This research suggests the utilisation of a Grey-DEMATEL based structural model to (i) determine the I4.0 adoption drivers, and (ii) evaluate the causal relations among the drivers.

Notably, nine of the most relevant I4.0 sustainability-oriented drivers are identified using literature resources and inputs from experts. Further, Grey-DEMATEL contributed in defining the causal interactions among the drivers under vague and unclear conditions. The data for this work was collected from industry and academic experts, considering one of the current leading emerging economies, i.e. India, for its applicability. The six drivers namely (1) Government supportive policies (D8), (2) Development of infrastructure and IT based facilities (D3), (3) Management support and effective governance (D2), (4) Collaboration and transparency among supply chain members (D1), (5) Improved information sharing system and resource development (D5) and (6) Workforce knowledge and expertise in managing resources (D7) were categorised as cause group drivers; and three drivers namely (7) Adoption of innovative business models (D9), (8) Reduction in waste and improved cost efficiency (D6) and (9) Competitiveness (D4) were categorised as effect group drivers.

6.1 Unique Contributions

The main contributions of the present work are:

- The contribution of this study is unique as in the literature very limited discussion is available in regards to the investigation and definition of drivers of I4.0 for achieving sustainability in SCs, within the context of an emerging economy.
- This research work identified nine key drivers of I4.0 to diffuse sustainability in SCs through literature and experts' feedback in the context of an emerging economy i.e. India.
- As a methodology contribution, the Grey-DEMATEL approach was used to determine the cause-effect relationship among the identified drivers under vague and unclear surroundings. Additionally, the study developed an interrelationship diagram of the drivers, which will assist managers in understanding the influence of each driver, which further may help to make effective planning for achieving high triple bottom (ecological-economic-social) sustainability in a SC context.

The study has few limitations; those will provide future research directions to researchers. The selection of drivers was challenging. Some more drivers may be included/removed from the list in the future. This research has been conducted in an emerging nation context, considering experts from India. The findings may be extended to other nations with marginal modifications. The drivers may also be evaluated for their priority in future works. Grey-DEMATEL is used to determine interrelationships among drivers but the weights of each driver can be calculated in future research by using other Multi-Criteria Decision Making (MCDM) methods like Analytic Hierarchy Process (AHP); Analytic Network Process (ANP); Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Best-Worst Method (BWM). In this research, the independence of the criteria could not be tested statistically. In future research, interdependence of the drivers may be tested through Structural Equation Modelling (SEM). Multi-areas study can determine the role of drivers in the implementation of I4.0. Finally, an empirical study can be conducted to measure the impact of adopting I4.0 on sustainability in a SC context.

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Appendix A

The modified-CFCS a three-step procedure:

(i) Lower and upper normalized values.

$$\underline{\otimes}\dot{A}_{xy} = \left(\underline{\otimes}\check{A}_{xy} - \min_{y} \underline{\otimes}\check{A}_{xy}\right)/\Delta_{min}^{max} \qquad (A.1)$$

Where $\underline{\otimes}\dot{A}_{xy}$ represents the normalized lower limit value of the Grey number $\underline{\otimes}\check{A}_{xy}$

$$\overline{\otimes}\dot{A}_{xy} = \left(\overline{\otimes}\check{A}_{xy} - \min_{y} \overline{\otimes}\check{A}_{xy}\right)/\Delta_{min}^{max} \qquad (A.2)$$

Where $\overline{\otimes}\dot{A}_{xy}$ represents the normalized upper limit value of the Grey number $\overline{\otimes}\check{A}_{xy}$

$$\Delta_{min}^{max} = \max_{y} \overline{\otimes}\check{A}_{xy} - \min_{y} \underline{\otimes}\check{A}_{xy} \qquad (A.3)$$

(ii) Calculate total normalized crisp value

$$B_{xy} = \left(\frac{\left(\underline{\otimes}\dot{A}_{xy}(1 - \underline{\otimes}\dot{A}_{xy}\right) + (\overline{\otimes}\dot{A}_{xy} \times \overline{\otimes}\dot{A}_{xy})}{\left(1 - \underline{\otimes}\dot{A}_{xy} + \overline{\otimes}\dot{A}_{xy}\right)}\right) \qquad (A.4)$$

(iii) Compute final crisp values

$$B_{xy}^{*} = \left(\min \underline{\otimes}\dot{A}_{xy} + (B_{xy} \times \Delta_{min}^{max})\right) \qquad (A.5)$$

Where $B = \left[B_{xy}^{*}\right]$ $\qquad (A.6)$

Appendix B

Table B1: Grey DEMATEL scale

Linguistics assessment	Assigned Grey numbers	Crisp values
No influence (N)	(0, 0.1)	0
Very low influence (VL)	(0.1, 0.3)	1
Low influence (L)	(0.2, 0.5)	2
Medium influence (M)	(0.4, 0.7)	3
High influence (H)	(0.6, 0.9)	4
Very high influence (VH)	(0.9, 1.0)	5

Table B2: The crisp relation matrix for key drivers

Drivers	D1	D2	D3	D4	D5	D6	D7	D8	D9
D1	0.00	0.69	0.76	0.48	0.46	0.78	0.57	0.57	0.78
D2	0.60	0.00	0.76	0.41	0.57	0.57	0.57	0.83	0.30
D3	0.82	0.48	0.00	0.76	0.83	0.57	0.30	0.30	0.30
D4	0.32	0.41	0.18	0.00	0.30	0.30	0.13	0.13	0.13
D5	0.60	0.76	0.41	0.76	0.00	0.30	0.57	0.83	0.51
D6	0.49	0.76	0.69	0.41	0.57	0.00	0.57	0.36	0.30
D7	0.43	0.41	0.41	0.76	0.51	0.57	0.00	0.51	0.83
D8	0.54	0.76	0.76	0.76	0.57	0.83	0.83	0.00	0.57
D9	0.60	0.76	0.41	0.48	0.30	0.30	0.30	0.57	0.00

Table B3: T-matrix for key drivers

Drivers	D1	D2	D3	D4	D5	D6	D7	D8	D9
D1	0.38	0.45	0.42	0.41	0.45	0.51	0.45	0.47	0.47
D2	0.46	0.34	0.41	0.39	0.46	0.47	0.44	0.50	0.39
D3	0.46	0.38	0.27	0.40	0.46	0.43	0.36	0.38	0.35
D4	0.21	0.20	0.16	0.14	0.20	0.21	0.17	0.18	0.16
D5	0.45	0.44	0.35	0.42	0.34	0.41	0.43	0.49	0.41
D6	0.39	0.40	0.36	0.34	0.40	0.31	0.39	0.37	0.34
D7	0.39	0.37	0.33	0.40	0.40	0.42	0.30	0.41	0.43
D8	0.49	0.49	0.44	0.47	0.49	0.55	0.52	0.40	0.47
D9	0.38	0.37	0.30	0.32	0.33	0.34	0.32	0.38	0.26