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SMART SUPPLY CHAIN DRIVERS MEASUREMENT TOWARDS IMPROVING SUSTAINABLE PERFORMANCE UNDER INDUSTRY 4.0 NOTIONS

Dr. Mohit Tyagi, Associate Professor, Department of Production and Industrial Engineering
Punjab Engineering College (Deemed to be University), Chandigarh :: mohitmied@gmail.com

ABSTRACT

In the last few years, circular economy (CE) and Industry 4.0 (I4.0) disruptive concepts have gained significant attention among researchers, practitioners, and policy-makers. Organizations implementing sustainable supply chain management (SSCM) strategies aim to mitigate negative environmental and social effects within their supply chains (SCs). Technologies from the I4.0 era have proven effective in addressing these challenges by modernizing SC technology. I4.0 uses cutting-edge technology to usher in a digital and sustainable revolution in SC. Prioritizing sustainable growth and utilizing technologies like Big Data, Internet of Things (IoT), blockchain technology (BT), and artificial intelligence (AI) should be a top priority for organizations to create smart and resilient SCs that enhance sustainable performance. This study aims to recognize key drivers of smart supply chains (SSCs) to enhance sustainability. To achieve this, a list of key drivers was compiled through a literature review and discussions with experts, and further analyzed using the Fuzzy DEMATEL technique. The Fuzzy input data about selected key drivers were aggregated by using the defuzzification approach to transform them into crisp scores to solve the impreciseness and vagueness. The findings of this study can assist managers, stakeholders, and researchers in identifying key drivers of SSC to enhance sustainability.

Keywords Circular economy (CE), Industry 4.0 (4.0), sustainable supply chain management (SSCM), smart supply chain (SSC), fuzzy DEMATEL

I. Introduction & background

The utilization of natural resources has escalated due to economic growth, enhanced living standards, and a burgeoning population [1,2]. The shortage of these resources drives up input costs, making products less sustainable in the market. Global supply chains (SCs) are under significant pressure from regulatory bodies to ensure sustainability across all operational activities [3]. SCs are crucial for enhancing organizational performance and encompassing the entire product life cycle, from raw material procurement to customer-level consumption [4]. Organizations are being forced by social and environmental concerns to shift from linear to circular processes to avoid throwing away consumer or end-of-life items in an inefficient manner. Circular economy (CE) approach, which encompasses the principles of Reduce, Reuse, and Recycle (3Rs), serves as a tool to enhance sustainability within operations [5,6]. Adopting the CE notion in the supply chain perspective is necessary for the sustainability viewpoint [7]. By incorporating Industry 4.0 (I4.0) with CE principles, resources can be repurposed several times for various applications [8].

In the era of industrial digitalization, the connection between Industry 4.0 (I4.0) and circular CE has consistently facilitated the investigation of diverse methods to attain ecological sustainability targets [9]. I4.0 has expedited the removal of obstacles to achieving circularity, with digitalization increasingly catalyzing the design and implementation of cleaner production methods [10,11]. The principles of I4.0 facilitate both vertical and horizontal integration of intelligent production systems by leveraging advanced information and communication technology and data aggregation methods [12,13]. This integration simplifies the application of collaborative SC business models essential for managing inventories in accordance with real-time consumption and demand forecasts [14].

These days, there is a noticeable increase in the usage of digital technology [6]. The swift and proficient advancement of smart technologies, including artificial intelligence (AI), blockchain, cloud computing, and IoT, has driven SC innovation, leading to the emergence of "smart supply chains

(SSCs)"[15,16]. Frank et al. [17] classified the idea of I4.0 into two primary parts the basic technologies and the front-end were among them. Initiatives related to smart working, smart goods, SSCs, and smart manufacturing are all included in the front-end technology dimension. On the other hand, big data, analytics, cloud services, and the IoT are examples of base technology components. With more products embedded with sensors, they offer improved visibility, automation, and intelligent decision-making capabilities [18].

SSC works like a holistic entity, the smaller independent entities need to function similarly to the interconnected physical assets seen in a smart environment—that is, as linked platforms. When one variable changes for a single entity, the other related entities must respond collectively and with a countermeasure [19,20]. These days, technology plays a major role in creating sustainable businesses [21]. It is a large-scale business approach. Improving response and production times while cutting expenses and waste are the objectives [22]. This trend towards SSCs presents significant opportunities for cost reduction and sustainability enhancement.

With the aforementioned theme in consideration, the present study is directed toward a SSC, aiming to recognize and analyze the key drivers to enhance the sustainability of SSC. In pursuit of this objective, seven key drivers have been identified through a literature review and expert consultations. The identified drivers, as mentioned below, have been analyzed within the Fuzzy environmental framework employing the Fuzzy DEMATEL approach.

The current research is organized as follows: Section 2 outlines the step-by-step procedure of the Fuzzy DEMATEL approach and numerical representation. The findings and discussion are presented in Section 3. The implications, conclusion, and future directions are discussed in sections 4 & 5.

1.1 Key drivers of smart supply chain

Data sharing platform (DS1): The data sharing platform emphasizes the importance of designing and developing intelligent platforms and utilizing blockchain technology. This approach aims to enhance integration among SC members, thereby improving communication, data sharing security, flexibility, and productivity [23,24].

Infrastructure to technology and information exchange (DS2): The means by which communications are sent are called communication tools. Information can be shared, retrieved, and stored via IT systems for processing outside of corporate boundaries [25,26,27].

Big data-driven decision-making system (DS3): BDA aids in problem-solving and planning for producers. Due to its ability to detect problems with systems and procedures in real time, big data has a big influence on corporate choices. Additionally, it can help in making tough decisions in the face of unanticipated circumstances and possible dangers [28,29,30].

Optimization of logistics operations (DS4): Implementing I4.0 technologies in logistics is advised to optimize material volume and flow, minimize erroneous deliveries and waiting times, reduce pollutant gas emissions from transportation, and enhance the proficient use of the transportation [31,32, 6].

Lessening waste and enhanced cost efficiency (DS5): I4.0 reduces waste generation and improves SC cost efficiency [33]. Although the initial adoption of I4.0 technologies may raise an organization's costs, the long-term economic gains will ultimately enhance overall business performance [34].

Association and transparency among SC stakeholders (DS6): To achieve sustainability within SC, manufacturing organizations must foster collaboration among various stakeholders [35]. This driver pertains to how I4.0 can facilitate the creation of long-term sustainable relationships among various SC members [36].

Healthier human resource management (DS7): This driver contains components that support I4.0-based, healthier human resource management. It enhances individuals' professional development, both technically and behaviorally, and improves performance and job satisfaction [37,38].

II. Research methodology & numerical representation

To address complexities like vagueness and uncertainties in data, decision-makers use linguistic terms like "very low," "low," "medium," "high," and "very high" to express their opinions. These linguistic terms are then converted into fuzzy numbers for further evaluation. Unlike crisp sets based on Boolean logic, which only take into account values of 0 (false) or 1 (true), fuzzy sets, which are derived from fuzzy logic, give a degree of membership to each integer within the interval [0, 1]. A fuzzy set Ã is defined as a subset of a universe of discourse X, consisting of ordered pairs, and is characterized by a membership function $\mu_{\tilde{A}}$ *(X)*. This function maps elements of *X* to values in the interval [0, 1], where $\mu_{\tilde{A}}$ *(x)* = 1 indicates full membership in Ã, and $\mu_{\tilde{A}}$ *(x)* = 0 indicates non-membership in the fuzzy set *Ã*.

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x))\}, \quad x \, \epsilon \, X \qquad (1)$$

Triangular Fuzzy Numbers (TFNs) are often favored in real-world applications because of their computational simplicity. A TFN can be represented as $\widetilde{N}_a$= (l_a,m_a, n_a). The membership function μÃ(x) of a TFN can be expressed as follows:

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x \le l_a \\ \frac{x-l_a}{m_a-l_a}, & l_a \le x \le m_a \\ \frac{n_a-x}{n_a-m_a}, & m_a \le x \le n_a \\ 0, & x > n_a \end{cases} \qquad (2)$$

Where l_a,$m_a$and $n_a$are the real numbers with relationship $l_a > m_a > n_a$.

As previously mentioned, human judgments inherently involve uncertainty, which requires fuzzy aggregation methods that include a defuzzification process. In current study, the Converting Fuzzy Data into Crisp Scores (CFCS) method was used to address this uncertainty. The CFCS method establishes fuzzy ranges for maximum and minimum values, resulting in a crisp score calculated as a weighted average [39].

Consider, $\widetilde{N}_{ij}^{p}$ = $(l_{ij}^{p}, m_{ij}^{p}, n_{ij}^{p})$ where *p =1,2,.....,r*, the mean influence of i^{th} criterion over the j^{th}criterion.

$$\widetilde{N}^{n} = \begin{bmatrix} 0 & \widetilde{N}_{12}^{p} & \widetilde{N}_{13}^{p} & \dots & \widetilde{N}_{1h}^{p} \\ \widetilde{N}_{21}^{p} & 0 & \widetilde{N}_{23}^{p} & \dots & \widetilde{N}_{2h}^{p} \\ . & . & . & . & . \\ . & . & . & . & . \\ \widetilde{N}_{h1}^{p} & \widetilde{N}_{h2}^{p} & \widetilde{N}_{h3}^{p} & \dots & 0 \end{bmatrix} \qquad (3)$$

where *h = 1, 2,….q*, denotes the number of criteria and *r* represents the number of respondents.

In this study, the analytical analysis to assess the impact or influence that each factor or variable has on others involved collecting experts' opinions through a questionnaire-based survey. The experts were from manufacturing industries and various engineering and academic institutions. Structured and semi-structured brainstorming sessions with experts ensued after the questionnaire, which was organized using the scale presented in Table 2. The purpose of these meetings was to do analysis and get feedback on the relative importance of the characteristics that were found. By following this, a questionnaire was sent to one hundred twenty-five experts, with ninety-seven responses was received. Their opinions were collected in linguistic form using equation (3).

Experts' linguistic data are converted into TFNs and combined using CFCS defuzzification, resulting in individual defuzzified matrices. These matrices are averaged to form the direct-relation matrix (Table 2). The Fuzzy DEMATEL algorithm is used to normalize this matrix; however, the normalized matrix is omitted due to space constraints. Subsequently, the total relation matrix is structured (Table 3). 'Prominence' (M + N) and 'relation' (M - N) values are calculated from the row sums (M) and column sums (N), as summarized in Table 4. A cause-and-effect diagram is then created based on these values (Figure 1).

Table 1: Fuzzy linguistic scale for evaluation [39]

Linguistic term	Influence score	Triangular fuzzy number (TFNs)
No influence (No)	0	(0,0.1,0.3)
Very low influence (VL)	1	(0.1,0.3,0.5)
Low influence (L)	2	(0.3,0.5,0.7)
High influence (H)	3	(0.5,0.7,0.9)
Very high influence (VH)	4	(0.7,0.9,1.0)

Table 2: Average direct relation matrix

	DS1	DS2	DS3	DS4	DS5	DS6	DS7
DS1	0.000	0.500	0.452	0.405	0.357	0.452	0.357
DS2	0.829	0.000	0.829	0.829	0.875	0.783	0.737
DS3	0.500	0.690	0.000	0.500	0.500	0.500	0.500
DS4	0.690	0.690	0.690	0.000	0.737	0.690	0.643
DS5	0.405	0.265	0.359	0.452	0.000	0.311	0.219
DS6	0.783	0.737	0.783	0.829	0.737	0.000	0.783
DS7	0.311	0.311	0.310	0.125	0.217	0.171	0.000

Table 3: Normalized direct matrix

	DS1	DS2	DS3	DS4	DS5	DS6	DS7
DS1	0.000	0.102	0.093	0.083	0.073	0.093	0.073
DS2	0.170	0.000	0.170	0.170	0.179	0.160	0.151
DS3	0.102	0.141	0.000	0.102	0.102	0.102	0.102
DS4	0.141	0.141	0.141	0.000	0.151	0.141	0.132
DS5	0.083	0.054	0.074	0.093	0.000	0.064	0.045
DS6	0.160	0.151	0.160	0.170	0.151	0.000	0.160
DS7	0.064	0.064	0.063	0.026	0.045	0.035	0.000

Table 4: Total relation matrix

	DS1	DS2	DS3	DS4	DS5	DS6	DS7
DS1	0.173	0.251	0.253	0.233	0.237	0.231	0.228
DS2	0.447	0.277	0.439	0.418	0.447	0.393	0.408
DS3	0.305	0.318	0.206	0.284	0.300	0.272	0.288
DS4	0.386	0.364	0.379	0.236	0.387	0.345	0.358
DS5	0.214	0.179	0.202	0.209	0.134	0.177	0.170
DS6	0.427	0.397	0.420	0.406	0.413	0.244	0.406
DS7	0.157	0.149	0.154	0.115	0.138	0.117	0.090

Table 5: The score of each driver and related values for cause and effect groups

	M	N	M+N	M-N
DS1	1.569	2.109	3.678	-0.540
DS2	2.764	2.109	4.873	0.656
DS3	1.797	1.934	3.731	-0.138
DS4	2.399	2.054	4.453	0.344
DS5	1.256	1.900	3.156	-0.644
DS6	2.651	2.055	4.706	0.595
DS7	0.897	1.780	2.677	-0.883

III. Results & discussion

The prioritization of recognition of key drivers of SSC to enhance sustainability is determined by the (M + N) values in Table 5, with higher values indicating greater importance. The importance rating order is: DS2 > DS6 > DS4 > DS3 > DS1 > DS5 > DS7. The key driver, " Infrastructure to technology and information exchange (DS2)", has the highest importance rating 4.873, making it the most crucial. On the other hand, “Healthier human resource management (DS7)” has the lowest importance rating with a value of 2.677, making it the least vital driver. However, these drivers boost productivity and efficiency, helping to make SSC more sustainable by reducing inefficiencies in resource loops.

Using the cause and effect diagram (Fig. 1) and visualizing the (M-N) values, these drivers are classified into their respective cause and effect groups namely: Infrastructure to technology and information exchange (DS2), Association and transparency among SC stakeholders (DS6), and Optimization of logistics operations (DS4) have positive (M-N) values, and falls in the cause category group hence these drivers exert more influence on other drivers. In contrast, drivers: Big data-Driven decision-making System (DS3), Data sharing platform (DS1), Lessening waste and enhanced cost efficiency (DS5), and Healthier Human resource management (DS7) have negative (M-N) values and fall in the effect group and are influenced by cause group drivers.

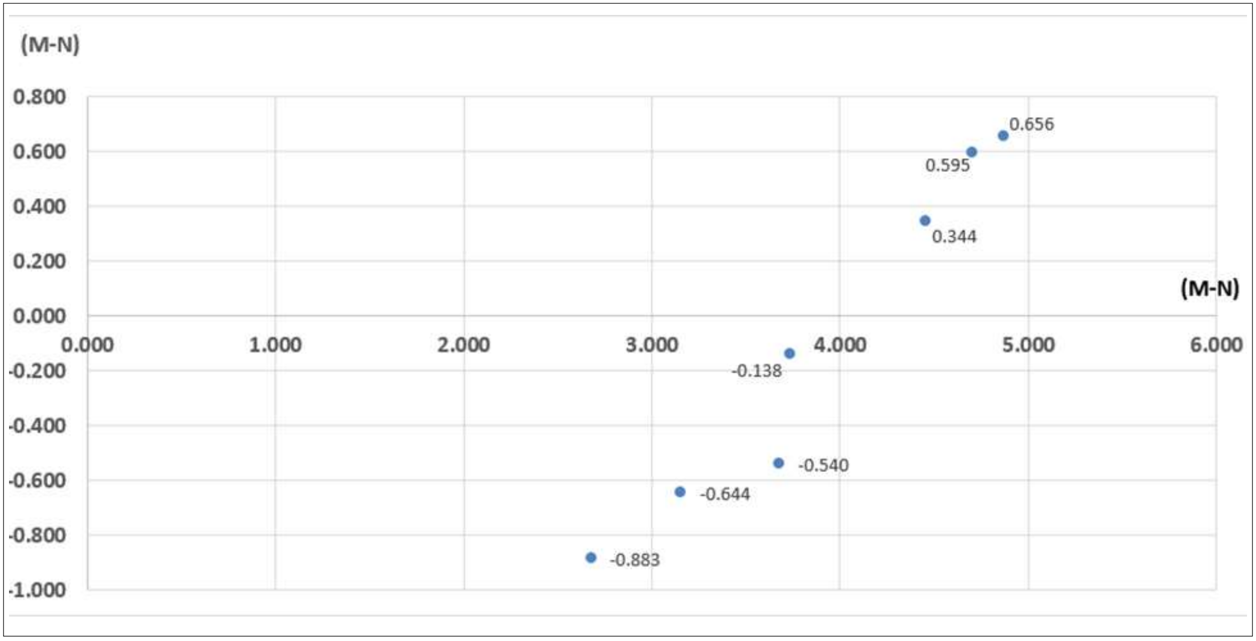

Fig. 1: Cause and effect diagram

IV. Implications

The present study possesses a strong theoretical and practical contribution to the areas of smart supply chain and sustainability. The implications of this study for researchers and practitioners, as well as the societal benefits of the proposed model, are discussed in the subsequent sub-sections.

- The ongoing environmental deterioration and resource scarcity have prompted researchers and industry professionals to develop and implement the essential drivers for the adoption of SSC in industry.
- It is challenging to integrate all the SSCs' drivers within an organization. Consequently, the priority order derived from the application of Fuzzy-DEMATEL enhances practical implementation.
- The priority of SSCs' drivers helps industry experts to develop innovative strategies in the starting phase itself. It will minimize the likelihood of failure and raise the probability of success in SSC adoption.

V. Conclusion and Future Scope

The current study aims to recognize and analyze the key drivers of SSC to enhance the sustainability towards I4.0. To achieve this, an extensive literature review was conducted, and opinions of various experts were taken to gather insights on this topic. The present study recognized and analyzed seven key drivers of SSC using Fuzzy DEMATEL technique. The analysis reveals that drivers within cause group particularly “Infrastructure to technology and information exchange (DS2)”, “Association and transparency among SC stakeholders (DS6)”, and “Optimization of logistics operations (DS4)” significantly contribute to achieving the objective and on the other hand drivers within effect group “Big data-driven decision-making system (DS3)”, “Data sharing platform (DS1)”, “Lessening waste and enhanced cost efficiency (DS5)”, and “Healthier human resource management (DS7)” are influenced by the identified drivers in the cause group. However, this study has certain limitations that present opportunities for future research. Future studies could use alternative MCDM techniques for analysis instead of relying solely on the Fuzzy DEMATEL approach.

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