Chapter 6

I4.0 ADOPTION: SUPPLY CHAIN RELIABILITY AND SUSTAINABILITY

6.1 Introduction

Government policies such as investment in infrastructure by providing 5G networks, high-speed internet, and smart grid services can support and help accelerate the adoption of I4.0 in SCs. In addition, tax incentives and policies to provide data privacy and cybersecurity can help ensure that the benefits of I4.0 technologies are not offset by the associated risks (Caiadoet al., 2022). The adoption of I4.0 in SCs can also automate the production systems so that they can quickly and efficiently adapt to market dynamics by producing high product variety and volume. By automating the production processes the dependency on conventional energy resources can also be minimized. Automated systems and smart contracts to use renewable energies with the help of smart grid technologies can boost performance with a reduction in carbon emissions. It facilitates organizations to achieve sustainability goals, reduce environmental impacts, and improve energy efficiency. Smart grids, sustainable manufacturing, and circular economy can also be integrated into SCs by adopting I4.0. In addition, the integration of I4.0 into the SCs can help companies build a reliable and resilient supply chain by improving efficiency, reducing errors, and providing real-time visibility and control over the SC, which can help companies to better manage their SC and respond to disruptions with increased performance, customer satisfaction, and reliability (Zhou et al., 2022).

By addressing integration issues, enabling benchmarking in the context of I4.0 adoption can expedite the process of adoption. A systematic approach to identifying and evaluating these enablers can offer a framework for progressive adoption. Comprehending the complex interrelationships among these enablers can additionally facilitate an efficient adoption voyage. SCs are complex networks with many different stakeholders, and it can be difficult to bring them all together on one platform. It necessitates large infrastructure investments that are compatible, but more crucially, it necessitates the commitment of management to these expenditures. Persuading stakeholders to invest in I4.0 becomes a difficult task if the advantages of its adoption are not well understood. Furthermore, a successful adoption process may encounter challenges due to a lack of familiarity with new practices, which emphasizes the significance of providing customized training at different organizational levels.

The available research on I4.0 adoption in SC discusses the barriers and enablers of adoption. However, the exploration of I4.0 adoption in the context of SC sustainability and building a reliable SC is sparse in the literature. More studies are needed to explore these relations so that a comprehensive adoption framework can be suggested to the SCs. To address this research gap this study aims to explore the following Research Questions (RQs):

RQ 1: What are the benchmarking enablers of I4.0 for SC sustainability to build a reliable SC?

RQ 2: What are the interrelations among benchmarking enablers of I4.0 for SC sustainability to build a reliable SC?

RQ 3: What is the adoption priority of benchmarking enablers of I4.0 for SC sustainability to build a reliable SC?

To address RQs, this study explores the I4.0 enablers for SC sustainability to build a reliable SC with the following Research Objectives (ROs):

RO 1: To identify the benchmarking enablers of I4.0 for SC sustainability to build a reliable SC.

RO 2: To identify the interrelations among benchmarking enablers of I4.0 for SC sustainability to build a reliable SC.

RO 3: To suggest the adoption priority of benchmarking enablers of I4.0 for SC sustainability to build a reliable SC.

To accomplish the aforementioned ROs, the benchmarking enablers of I4.0 and SC sustainability were initially examined. In addition, a case study of MSMEs implementing I4.0 technology was selected. On the creation of a hybrid system based on POMETHEE-II, AHP, and DEMATEL, the suggestions of experts were gathered. In this study, the AHP approach was used to determine the effect strength of the enablers of I4.0, the DEMATEL technique was used to uncover relationships between the enablers of I4.0, and PROMETHEE-II was used to rank the enablers with the greatest impact on I4.0 adoption in the SC.

Considering the limitations of the existing literature, it is necessary to pinpoint the major factors that influence the I4.0 adoption in SCs in terms of the social, economic, and environmental facets of sustainability. Government policies and collaboration among SC stakeholders are some key potential drivers of I4.0 adoption in SC (Luthra et al., 2020; Connor, 2020). In addition, the potential for corporate social responsibility and human resource management can promote sustainable practices and improve the well-being of workers and the environment by adopting I4.0. The policymakers and stakeholders should support the development of sharing economy initiatives that prioritize community participation, environmental sustainability, and social responsibility. Based on the deliberated literature survey, by using the keywords in connection to the supply chain, such as I4.0, enablers, benchmarking enablers, sustainability, and reliability, twenty benchmarking enablers are identified. Further, a questionnaire including these twenty enablers is circulated through a digital platform and discussed with experts. After that, a total of fifteen potential benchmarking enablers of I4.0 for SC sustainability to build a reliable SC are identified. Table 19 reflects the identified enablers with appropriate references. Table 19 reflects the identified enablers with appropriate references.

Table 19: Benchmarking enablers of I4.0 for SC sustainability to build a reliable SC

S. No.	Enabler	Description	References
1	Decentralization structure (E1)	The decentralized structure allows efficient decision-making at all levels of SC thus enhancing the responsiveness of the network.	(Thomas et al., 2016; Sajid et al., 2016; Biegańska, 2022)
2	Green energy systems (E2)	A green energy system employs digital and advanced technologies such as a smart grid to effectively monitor and regulate the transmission of electricity from diverse generation sources, encompassing both renewable and non-renewable forms, in order to cater to the fluctuating needs of end users while minimizing emissions.	(De Sousa, 2018; Kluczek, 2019; Biegańska, 2022)
3	Data security and handling (E3)	I4.0 technologies such as blockchain ensure the efficient and secured flow of data among all stakeholders thus enhancing the reliability and SC performance.	(Kamble et al., 2018; Thomas et al., 2016; Lin, 2018; Galati & Bigliardi, 2019; Kluczek, 2019; Connor, 2020)
4	Process innovation (E4)	Design and production of products through process innovation enhance the reliability and sustainability aspects of the SC.	(Khan et al., 2022; Jamwal et al., 2021)

5	Smart factory technologies (E5)	The adoption of smart factory technologies reduces energy consumption and minimizes errors thus helping to improve sustainability and reliability.	(Machado et al., 2020; Lin, 2018; De Sousa, 2018; Guo et al., 2022; Connor, 2020)
6	Scalability (E6)	Scalability of efficient processes and practices to produce services or products in a sustainable and reliable way throughout the SC.	(Machado et al., 2020; E. Machado et al., 2021)
7	Real-time monitoring (E7)	Real-time monitoring enhances the decision-making by quickly identifying the cause of errors and disruptions thus enhancing the reliability and sustainability of SC.	(Zhohov et al., 2018; Jamwal et al., 2021; Biegańska, 2022)
8	Customer and supplier integration (E8)	Customer and supplier integration provides coordinated and efficient decision-making related to inventory, collaborative planning, forecasting, replenishment, and the flow of physical resources thus enhancing the reliability and sustainability of SC.	(Kumar et al., 2020; Connor, 2020)
9	Government supportive policies (E9)	Governmental policies play a key role in supporting business organizations and providing the necessary support in the implementation of I4.0 technologies.	(Luthra et al., 2020; Tarigan et al., 2020)
10	Business process resilience (E10)	Business process resilience provides the necessary adaptability to unforeseen challenges and disruptions thus maintaining a high degree of reliability and sustainability in the SC.	(Agostini & Filippini, 2019; Connor, 2020),
11	Supply chain digitization (E11)	Digitization of the supply chain improves the data processing and analysis. It results in quick identification of errors and challenges.	(Thomas et al., 2016; Lin, 2018; Galati & Bigliardi, 2019; Agostini & Filippini, 2019; Luthra et al., 2020)
12	Information transparency (E12)	Information transparency maximizes the trust and reliability of SC. It also promotes sustainable practices by developing efficient relationships among stakeholders.	(Guo et al., 2022; Kamble et al., 2018)
13	Knowledge management and training (E13)	It helps to improve the adoptability of new technology and sustainable practices which result in the	(Leng et al., 2020; Kamble et al., 2018; De Sousa, 2018; Kluczek, 2019;

		enhancement of the SC performance and reliability.	Agostini & Filippini, 2019; Luthra et al., 2020)
14	Flexible manufacturing systems (E14)	Flexible manufacturing systems offer flexibility towards varying demand and change in customers' preferences in a reliable and sustainable way by incorporating technologies and innovation in the processes.	(Dohale et al., 2020; Luthra et al., 2020; Connor, 2020; Jamwal et al., 2021)
15	Top management commitment (E15)	The role of the top management commitment is crucial in the I4.0 adoption and implementation of reliable and sustainable practices among stakeholders.	(Tarigan et al., 2020; Jamwal et al., 2021)

6.2 Methodology

To evaluate the significance of suggested alternative solutions and assess a variety of interrelated and complex criteria using expert opinion, the Multi Criteria Decision Making (MCDM) method is employed. Either qualitative or quantitative factors are being considered. While quantitative criteria are recognized to be expert-independent, qualitative criteria are understood to be expert-dependent and may be subjective. This study employs the Analytical Hierarchy Process (AHP) to structure the complexity of benchmarking enablers of I4.0 hierarchically as it helps in evaluating multiple criteria. In addition, the AHP approach utilizes the pairwise comparisons technique thus assisting in the proper analysis of enablers (Teng et al., 2023). Further to understand the causal relations among enablers, the DEMATEL technique is employed as it is a powerful technique to analyze and visualize the intricate systems and to provide detailed insights into the interactions among enablers (Zhang et al. 2023). Further to obtain the preference and ranking of benchmarking enablers PROMETHEE II is used (Ridha et al., 2023). These methods are versatile and can be applied in various domains. In addition, they provide a robust framework for efficient decision making thus enabling the researchers to systematically understand the multiple criteria and complex interrelations among various factors. Table 19 was created after an extensive literature study and questionnaire circulated through a digital platform on benchmarking enablers of I4.0 for SC sustainability to build a reliable SC. The detailed steps of the methodology are presented in Figure 11.

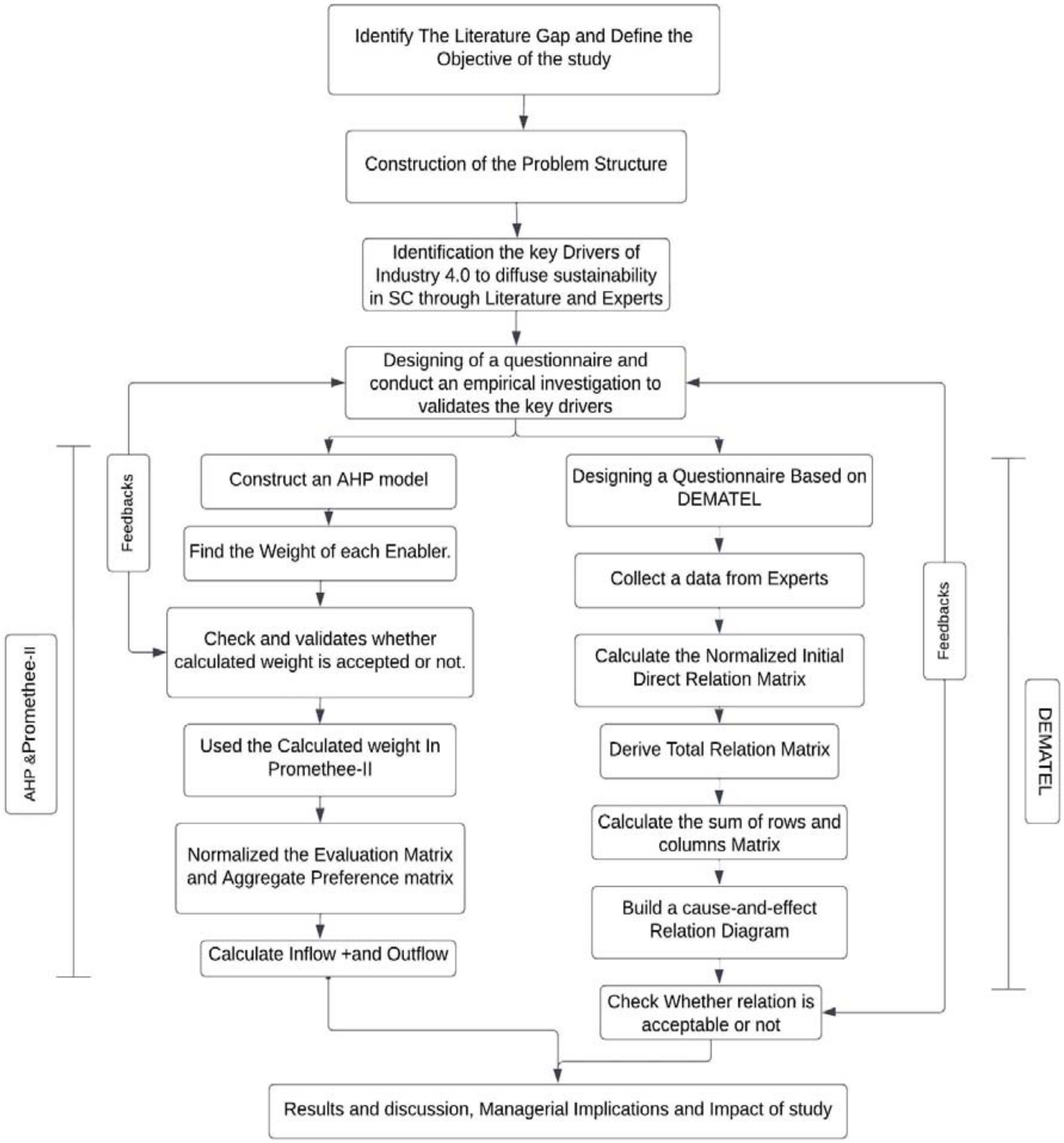

Figure 11: Research Framework

6.2.1 Data Collection, questionnaire design, and Delphi technique

To identify the benchmarking enablers of I4.0 for SC sustainability to build a reliable SC, an extensive literature review is performed. The selected enablers are further converted to a questionnaire that is circulated through a digital platform for screening and a total of 125 valid responses are received. Further, the identified enablers are presented to the experts and Delphi techniques are employed and 15 enablers are finalized. The experts are asked to provide the weights and interrelations among these enablers separately.

Table 20: Details of Experts

Respondent	For screening criteria	Average experiences (Years)	For weighting and interrelation among enablers	Average experience (Years)
Industry Expert	15	5	3	8
Academicians	35	4.5	2	9
Research Scholar	75	2.0	1	4

The process is repeated in multiple rounds until consensus among experts is reached. The experts were qualified in the field they assess and have relevant training. The detail of the experts is presented in Table 20 and the linguistic scale used and corresponding numerical values are presented in Table 21.

Table 21: Linguistic scales

Linguistic Scales	Numerical value
No impact	0
Very low impact	1
Low impact	3
Medium impact	5
High impact	7
Very high impact	9

6.2.2 Analytic Hierarchy Process (AHP)

The AHP technique is used to calculate the weight of I4.0 enablers. The pair-wise comparison was conducted using expert inputs. All the enablers were divided into five categories based on experts' input and discussions. For this, a pairwise comparison is performed among the potential enablers and their alternatives to measure the relative importance of each enabler. Pairwise comparison is a decision-making technique that compares the relative importance of two or more alternatives in relation to a specific criterion or factor (Caceoğlu et al., 2022). The pairwise comparison method depends on comparing each alternative to each subsequent alternative, one pair at a time, and assigning a weight to each alternative in the pair to indicate its relative importance (Boumaiza et al., 2022). As an example, the decision makers placed 3 for comparing the decentralization structure (E1) with the Supply chain digitization (E11), indicating that Supply chain digitization is three times more important than the decentralization structure. However, pairwise comparison cannot directly reveal the weight of each factor. To get the weight of each factor, it is necessary to normalize Table 19. AHP normalization involves converting the pairwise comparison matrix of enablers or alternatives into a consistent matrix from which the relative weights of the criteria or alternatives can be calculated (Morales Jr & de Vries, 2021).

Table 22: AHP scale

Linguistic Scales	Numerical values	Inverse Scale
Equal importance	1	1
Weak importance of one over another	3	1/3
Strong importance	5	1/5
Very strong importance	7	1/7
Absolute importance	9	1/9
Intermediate values	2,4,6,8	1/2, 1/4, 1/6, 1/8

Pairwise Comparison: The first step in the AHP process is to perform pairwise comparisons between the criteria and alternatives to determine their relative importance.

The formula for pairwise comparison is presented in equation (1).

$$w_{(i,j)} = 1/w_{(j,i)} \tag{1}$$

Where $w_{(i,j)}$ is the weight of criterion i relative to criterion j, and $w_{(j,i)}$ is the weight of criterion j relative to criterion i. These weights are represented on a scale from 1 to 9, with 1 indicating that the two criteria are equally important, and 9 indicating that one criterion is extremely more important than the other. The details are presented in Table 22. The pairwise comparison matrix is presented in Table 23.

*Table 23**:** Pairwise Comparison AHP-Matrix*

Enablers	E1	E11	E14	E4	E5	E6	E7	E8	E9	E10	E2	E12	E13	E3	E15
E1	1	3	3	7	3	5	3	3	3	3	7	5	7	5	4
E11	0.33	1	5	7	5	5	3	3	7	5	5	3	7	9	9
E14	0.33	0.2	1	7	7	5	3	3	5	7	5	5	5	7	6
E4	0.143	0.143	0.143	1	7	7	5	5	7	7	7	7	9	7	6
E5	0.33	0.2	0.143	0.143	1	5	3	3	5	5	5	5	5	5	4
E6	0.2	0.2	0.2	0.143	0.2	1	5	5	5	5	5	3	5	5	4
E7	0.33	0.33	0.33	0.2	0.33	0.2	1	5	3	5	3	3	3	5	4
E8	0.33	0.33	0.33	0.2	0.33	0.2	0.2	1	3	3	3	5	3	3	2
E9	0.33	0.143	0.2	0.143	0.2	0.2	0.33	0.33	1	7	5	5	3	5	4
E10	0.33	0.2	0.143	0.143	0.2	0.2	0.2	0.33	0.143	1	5	5	7	5	4

E2	0.143	0.2	0.2	0.143	0.2	0.2	0.33	0.33	0.2	0.2	1	3	5	5	4
E12	0.2	0.33	0.2	0.143	0.2	0.33	0.33	0.2	0.2	0.2	0.33	1	5	5	4
E13	0.143	0.143	0.2	0.111	0.2	0.2	0.33	0.33	0.33	0.143	0.2	0.2	1	5	4
E3	0.2	0.2	0.143	0.143	0.2	0.2	0.2	0.33	0.2	0.2	0.2	0.2	0.2	1	5
E15	0.25	0.111	0.1667	0.1667	0.25	0.25	0.25	0.5	0.25	0.25	0.25	0.25	0.25	0.2	1

Normalization: After performing pairwise comparisons, the weights are normalized to ensure that they add up to 1. The formula for normalization is presented in equation (2):

$$W_{(i)} = \sum_j w_{(i,j)}/n \qquad (2)$$

Where $W_{(i)}$ is the normalized weight of criterion i, $w_{(i,j)}$ is the weight of criterion i relative to criterion j , and n is the total number of criteria.

The global weights of the enablers are calculated with their respective ranks which are shown in Table 24.

6.2.3 DEMATEL (Decision Making Trial and Evaluation Laboratory)

The DEMATEL technique was used to calculate the relationship between enablers and their cause-and-effect intensities (Sun et al., 2023). The expert opinions were used to compare the relationships between the I4.0 enablers group. The direct relationship matrix was developed using the mean values obtained from the experts' as shown in Table 7 and Initial Pairwise Comparison Matrix is shown in Table 8.

Each of the k criteria is considered to have the ability to affect a different criterion but not itself. Finally, each m^{th} expert constructed n partitive initial direct influence matrices Z_m as shown in equation (3):

$$Z_m = [z_{ij}^m]_{k\times k} \qquad (3)$$

Where $[z_{ij}^m]$ is the expert's opinion of the magnitude to which criterion j is impacted by criterion i. There is a collection of partial matrices.

A direct influence matrix, Z = $[z_{ij}^m]_{k\times k}$ is produced by matrix aggregation and is provided in equation (4):

$$Z = \frac{1}{n}\sum_{m=1}^{n}[z_{ij}^m] \ , i, j = 1,2,3, \ldots k \qquad (4)$$

Normalized direct influence matrix X

$$X = [x_{ij}]_{k\times k} = \frac{Z}{s} \quad (5)$$

Where s is calculated by,

$$s = \left(max \sum_{j=1}^{k} z_{ij}\ , where\ 1 \le i \le k\ ;\ \ max \sum_{i=1}^{k} z_{ij}\ , where\ 1 \le j \le k\right) \quad (6)$$

Total Relation Matrix T-

Total relations Matrix $T = [t_{ij}]_{k\times k}$ is obtained by:

$$T = X(I - X) - 1, when \lim_{l\to\infty} X^{l} = [0]_{k\times k} \quad (7)$$

Where,

$$X = [x_{ij}^{m}]\ k \times k, 0 \le x_{ij}^{m} < 1,\ \ 0 < \sum_{j=1}^{k} x_{ij}^{m} \le 1\ and\ 0 < \sum_{i=1}^{k} x_{ij}^{m} \le 1 \quad (8)$$

And the sum of the items of at least one row or column equals one,

$$\lim_{l\to\infty} X^{l} = [0]_{k\times k} \quad (9)$$

The vectors R and C

$$R = [r_i]_{k\times 1} = \left[\sum_{i=1}^{k} t_{ij}\right]_{k\times 1} \quad (10)$$

$$C = [c_i]_{1\times k} = \left[\sum_{i=1}^{k} t_{ij}\right]_{1\times k}^{T} \quad (11)$$

Where, R_i is the matrix T's i-th row sum. It displays the total of the effects that are dispatched from parameter i to the other ones. Similar to that, C_j is the T matrix's j-th column sum. It displays the effects that each other parameter has on parameter j. Assume that I = j and that I j 1,2,3, ...k It is possible to get the relation indicator $(R_i - C_i)$. It displays an overall impact. Similar to this, the relation vector (R – C) shows the factor's overall impact on the system under study. Calculate the position indicator $(R_i + C_i)$.

The position vector (R + C) demonstrates the significance of the criteria in the examined system by reflecting the overall impact of each component on the system. Regarding (R – C), the fact that $(R_i - C_i) > 0$ indicates that a criterion has an impact on both the system and other criteria. The fact that $(R_i - C_i) < 0$ further suggests that criterion i is influenced by other criteria.

Table 24: Direct-indirect relationships and total relationship matrix

Enablers	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	**Sum of Ci**
E1	0.167	0.133	0.256	0.212	0.227	0.206	0.259	0.218	0.162	0.193	0.23	0.244	0.152	0.215	0.152	**3.026**
E2	0.15	0.092	0.166	0.173	0.201	0.123	0.154	0.152	0.162	0.179	0.169	0.147	0.099	0.127	0.118	**2.212**
E3	0.23	0.169	0.166	0.202	0.215	0.155	0.242	0.222	0.16	0.203	0.173	0.242	0.134	0.156	0.122	**2.792**
E4	0.204	0.142	0.217	0.134	0.209	0.171	0.193	0.175	0.182	0.2	0.166	0.22	0.138	0.182	0.166	**2.7**
E5	0.27	0.219	0.288	0.239	0.198	0.208	0.271	0.261	0.22	0.265	0.241	0.29	0.169	0.236	0.198	**3.572**
E6	0.207	0.123	0.203	0.155	0.169	0.101	0.22	0.161	0.13	0.16	0.181	0.204	0.121	0.142	0.117	**2.395**
E7	0.188	0.122	0.197	0.177	0.187	0.133	0.137	0.182	0.127	0.148	0.177	0.176	0.113	0.131	0.115	**2.31**
E8	0.203	0.133	0.215	0.192	0.18	0.172	0.216	0.136	0.141	0.197	0.191	0.233	0.133	0.143	0.132	**2.619**
E9	0.112	0.133	0.14	0.122	0.161	0.091	0.13	0.171	0.082	0.122	0.106	0.168	0.097	0.105	0.084	**1.824**
E10	0.235	0.207	0.267	0.224	0.243	0.17	0.265	0.231	0.222	0.172	0.222	0.23	0.184	0.204	0.185	**3.259**
E11	0.244	0.169	0.261	0.23	0.264	0.179	0.277	0.252	0.186	0.256	0.173	0.281	0.209	0.23	0.195	**3.405**

E12	0.137	0.09	0.171	0.119	0.14	0.112	0.17	0.125	0.144	0.128	0.124	0.113	0.096	0.114	0.105	**1.888**
E13	0.158	0.119	0.17	0.153	0.191	0.158	0.174	0.158	0.14	0.183	0.18	0.22	0.091	0.141	0.129	**2.365**
E14	0.217	0.149	0.246	0.205	0.22	0.146	0.23	0.176	0.16	0.214	0.222	0.233	0.171	0.132	0.173	**2.893**
E15	0.13	0.111	0.142	0.13	0.141	0.095	0.175	0.129	0.152	0.18	0.124	0.178	0.112	0.122	0.078	**1.998**
Sum of Ri	**2.722**	**2.112**	**3.106**	**2.667**	**2.946**	**2.219**	**3.112**	**2.749**	**2.37**	**2.8**	**2.677**	**3.178**	**2.02**	**2.378**	**2.07**	

6.2.4 PROMETHEE-II

To determine the ranking of measures in SC enablers in I4.0, the same panel of experts completes the second survey questionnaire in the PROMETHEE II stage. The initial pairwise comparison matrix is used to determine the relative importance or weights of the criteria. A square matrix compares each criterion to every other criterion in terms of their relative importance (Burak et al., 2022).

Calculate the net flow of each alternative by aggregating the preference functions for all criteria. The net flow represents the degree of preference of each alternative over the others considering all criteria.

Deviation function in PROMETHEE II: Pairwise comparisons are used to derive the deviations $d_j(\mathrm{a,b})$. The following results are achieved when experts. $g_j(\mathrm{a})$and $g_j(\mathrm{b})$ differ over a criterion j:

$$d_j(\mathrm{a,b}) = g_j(\mathrm{a}) - g_j(\mathrm{b}) \tag{12}$$

Aggregation of the preference function is determined by:

$$\pi(i,l) = \sum_{j=1}^{k} P_j(i,l) w_j \tag{13}$$

Where $P_j(i,l)$ is the preference function, W_j is the AHP-determined weight of the j-th criterion's relative relevance, and k is the anticipated number of criteria.

Outranking flows for alternatives: A positive or negative outranking flow is produced by n alternatives in PROMETHEE-II. The incoming flow demonstrates the shortcomings of the precautions and can be achieved by: $\emptyset^{-}(i) = \frac{1}{n-1} \sum_{l=1}^{k} \pi\,(l,i)$

(14)

The leaving flow shows the strength of the measures. It is obtained through:

$$\emptyset^{+}(i) = \frac{1}{n-1} \sum_{l=1}^{k} \pi\,(i,l) \tag{15}$$

The net outranking flow F(i) for each measure:

$$\emptyset(i) = \emptyset^{+}(i) - \emptyset^{-}(i) \tag{16}$$

Based on net outranking flow, the final ranking of measures is assumed. The higher net outranking flow $F(i)$ means the preferred measure.

Table 25: Initial Pairwise Comparison Matrix

Enablers	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15
E1	1	3	3	7	3.8	5	3	3	3.8	3.8	7.8	5	7.8	5.8	5.6
E2	0.33	1	5	7	5	6.6	3	3	7	5	4.2	3	7	6.6	7
E3	0.33	0.2	1	5.4	7.8	5	2.2	2.2	5	6.2	4.2	3.4	5.8	6.2	6
E4	0.14292	0.14292	0.2178	1	5.4	6.2	4.2	4.2	7	7	6.2	7	8.2	6.2	6
E5	0.278	0.2	0.1302	0.2178	1	4.2	3	3	5	4.2	5.8	5	5.8	5	4.8
E6	0.2	0.1644	0.2	0.1658	0.252	1	4.2	4.2	5	4.2	4.2	3	5	4.2	4
E7	0.33	0.33	0.598	0.252	0.33	0.252	1	4.2	3.8	4.2	3	3	3	4.2	4
E8	0.33	0.33	0.598	0.252	0.33	0.252	0.252	1	3.8	3.8	3	4.2	3	3	2.8
E9	0.278	0.1426	0.2	0.1426	0.2	0.2	0.278	0.278	1	6.2	5	5	3	5	4.8
E10	0.278	0.2	0.1658	0.1426	0.252	0.252	0.252	0.278	0.1658	1	5	5	6.2	5	4.8
E11	0.1302	0.252	0.252	0.1658	0.1768	0.252	0.33	0.33	0.2	0.2	1	3.8	5.8	5	4.8
E12	0.2	0.33	0.52	0.1426	0.2	0.33	0.33	0.252	0.2	0.2	0.278	1	5	5.8	5.6
E13	0.1302	0.1426	0.1768	0.1234	0.1768	0.2	0.33	0.33	0.33	0.1658	0.1768	0.2	1	5.8	5.6
E14	0.1768	0.252	0.1658	0.1658	0.2	0.252	0.252	0.33	0.2	0.2	0.2	0.1768	0.1768	1	5.8
E15	0.2	0.1666	0.16682	0.16682	0.2168	0.25	0.25	0.4	0.2168	0.2168	0.2168	0.2	0.2	0.1772	1

Table 26: Aggregate Preference Matrix

Enablers	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	ø+
E1	0	0.118845124	0.075101798	0.143517	0.012003	0.064958	0.021509	0	0.023846	0	0	0	0	0.000381	0	0.027068
E2	0.220519	0	0.043638244	0.139291	0.037962	0.052955	0.017534	0.008161277	0.037705	0.025782	0.005441	0	0	0	0	0.034646
E3	0.338988	0.205850673	0	0.177683	0.070545	0.088258	0.030607	0.006823967	0.023061	0.024618	0.003274	0.001383	0	0.000553	0	0.057156
E4	0.341625	0.235725415	0.11190461	0	0.026357	0.011109	0.049673	0.049672506	0.025749	0.026357	0.002242	0.022426	0	0.007619	0.011133	0.054211
E5	0.371695	0.295980067	0.166350604	0.187941	0	0.055162	0.043822	0.02628806	0.022079	0.002682	0.004404	0.017319	0.005085	0.003583	0.001158	0.070797
E6	0.447672	0.333995221	0.207086184	0.195715	0.078184	0	0.040444	0.048605418	0.064134	0.049309	0.014741	0.019102	0.007223	0.00436	2.94E-05	0.088859
E7	0.494697	0.389048621	0.239908804	0.324753	0.157318	0.130918	0	0.008161277	0.067535	0.060112	0.019945	0.015252	0.007223	0.003428	0	0.112841
E8	0.543255	0.449742872	0.286193132	0.39482	0.209851	0.209147	0.078228	0	0.069533	0.057368	0.022224	0.022972	0.014942	0.005714	0	0.139058
E9	0.553502	0.465686971	0.288831054	0.357297	0.192042	0.211076	0.124002	0.05593291	0	0.013764	0.016299	0.025452	0.005906	0.004131	0.002515	0.136261

E10	0.574 989	0.49909 68	0.33572 0065	0.403 237	0.217 978	0.241 584	0.161 913	0.08910 119	0.059 097	0	0.006 707	0.018 973	0.008 12	0.003 584	0.002 3	0.154 259
E11	0.675 8	0.57956 6548	0.41518 6938	0.479 933	0.320 511	0.307 826	0.222 556	0.15476 7904	0.162 442	0.107 518	0	0.026 709	0.004 481	0.011 028	0.015 028	0.204 903
E12	0.683 515	0.58184 1579	0.42101 2265	0.507 833	0.341 142	0.319 903	0.225 579	0.16323 1548	0.179 312	0.127 499	0.034 425	0	0.002 01	0.001 658	0.002 759	0.211 278
E13	0.731 307	0.62963 2806	0.46742 0377	0.533 198	0.376 699	0.355 816	0.265 341	0.20299 3612	0.207 557	0.164 438	0.059 988	0.049 801	0	0.011 778	0.016 53	0.239 559
E14	0.739 317	0.63726 1821	0.47560 2638	0.548 446	0.382 827	0.360 582	0.269 176	0.20139 3955	0.213 411	0.167 531	0.074 164	0.057 078	0.019 407	0	0.006 441	0.244 273
E15	0.744 758	0.64308 4413	0.48087 1984	0.557 783	0.386 224	0.362 074	0.271 57	0.20150 2819	0.217 617	0.172 069	0.083 987	0.064 002	0.029 982	0.012 263	0	0.248 693
ø-	0.438 92	0.35678 5819	0.23616 6394	0.291 262	0.165 273	0.163 022	0.107 174	0.07156 685	0.080 769	0.058 767	0.020 461	0.020 028	0.006 14	0.004 122	0.003 405	

6.3 Sensitivity analysis

To ensure the robustness of the obtained rankings, a sensitivity analysis was conducted, serving to assess the reliability of the methodology. This analysis involved various approaches, including adjusting the assigned weights to experts and adding or removing enablers from the list to observe the resulting rankings of benchmarking enablers (Pandey et al., 2023). In this study, sensitivity analysis was executed by removing enablers in three different scenarios. In the first case, the top-ranked enabler (i.e., E10) was removed, followed by the deletion of the mid-range enabler (ranked 7 i.e., E9) in the second case, and finally, the removal of the lowest-ranked enabler (ranked 15 i.e., E2) in the third case. The resulting rankings from these sensitivity analyses are presented in Table 27. The separate calculations are performed in each case using PROMETHEE II.

Table 27: Sensitivity analysis

Enablers	Original ranking	Case 1 rank (by deleting E10)	Case 2 rank (by deleting E9)	Case 3 rank (by deleting E2)
E1	13	11	12	13
E2	15	14	14	Not Available
E3	14	13	13	14
E4	11	10	9	10
E5	10	8	10	11
E6	8	9	7	8
E7	9	7	8	9
E8	12	12	11	12
E9	3	3	Not Available	3
E10	1	Not Available	1	1
E11	6	6	6	5
E12	2	1	2	2
E13	7	5	4	7
E14	5	4	5	6
E15	4	3	3	4

The obtained ranking shows that E10 holds the first rank in all cases except case 1 (where E10 is deleted) and E2 holds the last rank. In addition, there is a minute fluctuation in the respective ranking of other enablers which shows the robustness and reliability of the methodology.

6.4 Results

This study used a multi-method approach to analyze the benchmarking enablers of I4.0 for SC sustainability to build a reliable SC. In the first stage of the study, the AHP method is employed to obtain the global weights and ranking of the enablers. In stage 2, the DEMATEL approach is used to understand the causal relations among enablers. Further to identify the preference criteria and adoption priority PROMETHEE II is used. The global weights of AHP are integrated into PROMETHEE II to obtain the aggregate preference matrix. The finding of all three methods is presented further in the section.

6.4.1 Findings of AHP

In the first stage, an AHP is constructed to identify the weights of the benchmarking enablers of I4.0 for SC sustainability to build a reliable SC. As a result, it ensures that the decision maker's comparisons are consistent and meaningful and that the weights reflect their preferences accurately. The global weights and ranks of enablers obtained through the AHP method are presented in Table 11. The top benchmarking enablers of I4.0 for SC sustainability to build a reliable SC as per the global weights are Decentralization structure (E1), Supply chain digitization (E11), Process innovation (E4), Flexible manufacturing systems (E14), Smart factory technologies (E5), and Scalability (E6).

Table 28: Global Weights and rank of enablers

Enablers	**Weights**	**Rank**
E1	0.165803	1
E2	0.031213	11
E3	0.016762	14
E4	0.116594	3
E5	0.07894	5
E6	0.067904	6
E7	0.057688	7
E8	0.046405	8
E9	0.045726	9
E10	0.040717	10
E11	0.153965	2
E12	0.030401	12

E13	0.020395	13
E14	0.116061	4
E15	0.011427	15

6.4.2 Findings of DEMATEL

In the second stage of analysis, DEMATEL was used to identify the causal relationships between all of those enablers. In order to do this, a normalization matrix was created from the direct relationship matrix. This matrix is used to calculate the sum of the R and C vectors using the total relationship matrix. The directionality of the cause-and-effect relationships among the enablers was ascertained by examining the variations in the R and C values. DEMATEL identified 9 of the 15 enablers considered in this study as the cause and the remaining 6 as the effect. For example, the difference between the R and C values for Green Energy (E2) was 0.09913, putting it in the cause group, while the difference for Top Management Commitment (E15) was -0.07226, placing it in the effect group. Notably, enablers with R_i and C_i differences greater than zero were considered as causes, whereas those with negative differences were considered as effects (Khan et al., 2022; Maqbool & Khan, 2020).

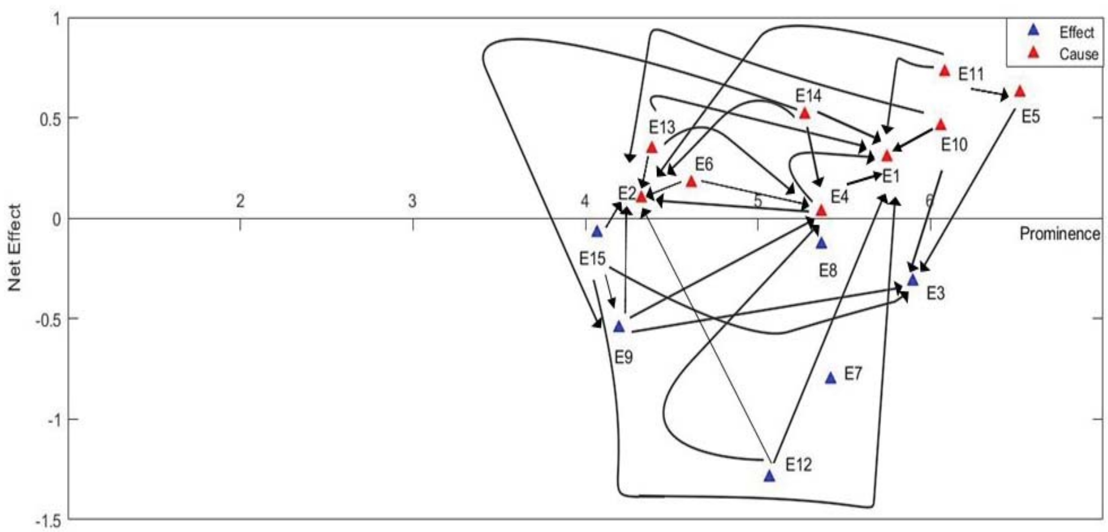

Figure 12: Cause and effective Relationship matrix

However, in Figure 12, the findings show that the Smart Factory technologies (E5) and supply chain digitization (E11), are at the top of the list and have the greatest positive effects on other enablers. Meanwhile, Information Transparency (E12) and Top Management Commitment (E15) have the least positive effects and are ranked last on the list. In addition, Real-time monitoring (E7), Customer and Supplier Integration (E8), and Government Supportive Policies (E9) have strong negative impacts. Although Scalability (E6) and Flexible manufacturing systems (E3) both have negative impacts, they rank higher than the aforementioned criteria. Indeed, the use of DEMATEL allowed for a thorough understanding of the causal relationships between the enablers, highlighting those that are essential for the implementation of I4.0 for SC sustainability to build a reliable SC. The details of such cause-effect relationships can be found in Table 29.

Table 29: Cause and Relationship Analysis

Enablers	R+C	R-C	Ranking
E1	5.74789	0.30363	6
E2	4.32393	0.09913	8
E3	5.89723	-0.31405	12
E4	5.36711	0.03221	9
E5	6.51817	0.62538	2
E6	4.61354	0.17555	7
E7	5.42124	-0.80199	14
E8	5.36787	-0.13016	11
E9	4.19399	-0.54580	13
E10	6.05969	0.45915	4
E11	6.08212	0.72750	1
E12	5.06624	-1.28962	15
E13	4.38487	0.34574	5
E14	5.27099	0.51554	3
E15	4.06738	-0.07226	10

6.4.3 Findings of PROMETHEE-II

The Aggregate Preference Matrix in Table 9 is created in the third stage to rank the enablers using positive and negative preferences. The PROMETHEE-II lists the following top five enablers in order of importance Supply chain digitization (E11), Decentralization structure (E1), Data security and handling (E3), Smart factory technologies (E5), and Real-time monitoring (E7). Alternatively, the bottom three enablers are Government supportive policies (E9), Flexible manufacturing systems (E14), and Top management commitment (E15). The rank matrix (inflow and outflow) with PROMETHEE-II is presented in Table 13. Overall, the result of this study shows a wide range of similarities in terms of different methodologies, which proves the credibility of this study.

Table 30: Rank Matrix (Inflow & Outflow) with PROMETHEE-II

Enablers	ø+	ø-	ø+ - ø-	Rank
E1	0.205769	0.026341	0.179427213	2
E2	0.083578	0.196214	-0.112636019	12
E3	0.201009	0.029883	0.171125704	3
E4	0.121559	0.112651	0.008908428	9
E5	0.195766	0.029784	0.165982202	4
E6	0.154878	0.060952	0.093925604	7
E7	0.170666	0.042718	0.127947737	5
E8	0.095539	0.193883	-0.09834393	11
E9	0.051343	0.438875	-0.387532032	13
E10	0.159705	0.05779	0.101915572	6
E11	0.217254	0.014008	0.203246077	1
E12	0.121681	0.110197	0.011483489	8
E13	0.100787	0.154683	-0.053895251	10
E14	0.024561	0.504116	-0.479554846	14
E15	0.023921	0.543143	-0.519221714	15

6.5 Discussion

With digitalization, businesses can automate and optimize their supply chain processes, which can reduce costs and improve the overall performance of the SC (Dash et al., 2019). Decentralization of the SC involves breaking down the traditional hierarchical structure and distributing responsibilities and decision-making across different stakeholders. This allows for greater agility and flexibility in responding to changes in demand or SC disruptions. Decentralization also improves communication and collaboration between stakeholders, which can lead to better decision-making and a more resilient supply chain. Information transparency involves the sharing of relevant data and information between different stakeholders in the supply chain. This can improve the accuracy and timeliness of decision-making, as well as enable stakeholders to anticipate and mitigate potential SC risks. Smart factory adoption involves the use of advanced technologies such as AI, IoT, and Robotics to create more intelligent and flexible manufacturing processes (Mantravadi et al., 2022). This can enable businesses to produce goods more efficiently and with greater customization, which can better meet the changing demands of customers (Xia et al., 2022). The Industrial Revolution 4.0 has provided businesses with the tools they need to build reliable supply chains that are more efficient, transparent, and secure. By leveraging these technologies, businesses can now better manage their inventories, optimize their production processes.