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iTDAF IETI Transactions on
Data Analysis and Forecasting

iTDAF | eISSN: 2959-0442 | Vol. 3 No. 2 (2025) | OPEN ACCESS

https://doi.org/10.3991/itdaf.v3i2.54749

PAPER

Industry 4.0 and Supply Chain Resilience: A Comprehensive Analysis of Technological Impacts

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ABSTRACT

This study proposes a novel framework to assess the impact of Industry 4.0 (I4.0) technologies on supply chain resilience (SCRE) enhancement. Recognising the dynamic nature of technological advancements and their influence on resilient supply chain (SC), the framework employs an integrated approach. Initially, relevant I4.0 technologies were identified through literature. The I4.0 technologies are then evaluated against critical SCRE network design requirements using integrated multi-criteria decision-making (MCDM) techniques. Results highlight node criticality as a paramount factor in SCRE, while ranking artificial intelligence (AI) as the most impactful I4.0 technology, followed by autonomous vehicles (AV) and digital twin (DT). This study provides a robust and quantifiable roadmap for understanding the role of specific I4.0 technologies in bolstering SCRE.

KEYWORDS

Industry 4.0, supply chain resilience, machine learning, artificial intelligence, big data analytics

1 INTRODUCTION

The flow of information and goods across the border between organisations has led to increased interconnectedness in supply chains (SCs) [1] and, at the same time, rising concerns on disrupt risks [2]. Operation management has adopted the concept of resilience [3]. Supply chain resilience (SCRE) actually deals with readiness and capability for SC to moderate the consequences of the risk events that occur to regain the prior state, or to transit to the better state after disruption [4].

I4.0 is a new technological breakthrough that can impact multiple industries and alter the way goods are produced, sold, and maintained. I4.0 indeed provides an intelligent formation that self-excavates and self-develops under the support of human participation, such as consumer order or input, yet would not require human mediation and supervision in most cases [5]. I4.0 promises to enhance SC performance and bolster its resilience against disturbances [6]. Due to the pivotal role of I4.0 technologies throughout the crisis and the swiftly evolving business

Kumar, D., Soni, G. (2025). Industry 4.0 and Supply Chain Resilience: A Comprehensive Analysis of Technological Impacts. *IETI Transactions on Data Analysis and Forecasting (iTDAF)*, 3(2), pp. 33–49. https://doi.org/10.3991/itdaf.v3i2.54749

Article submitted 2025-02-06. Revision uploaded 2025-03-28. Final acceptance 2025-04-11.

landscape, companies are increasingly seeking their adoption. I4.0 technology can improve visibility and foster trust and collaboration throughout the SC [7], [8].

There are very few studies that demonstrate the impact of I4.0 on SCRE and identify which technologies have a greater impact. Like, Spieske et al. [9] have investigated the potential of I4.0 technologies to enhance SCRE in the aftermath of the COVID-19 pandemic. This study developed 13 future-oriented projections concerning the application of I4.0 technologies in SCs. However, a significant gap remains in the literature regarding which specific I4.0 technologies have the most substantial impact on SCRE. Therefore, the objective, of this study are:

- To identify and assess the key I4.0 technologies that significantly impact SCRE, particularly in response to disruptions.
- To evaluate and compare the relative impact of different I4.0 technologies on SCRE, identifying which technologies have the highest influence in enhancing resilience against disruptions.

The paper is structured as follows: The second section comprises the literature review, the third section outlines the study methods, followed by the results section, and concludes with the paper's conclusion.

2 LITERATURE REVIEW

The initial segment will examine how I4.0 technologies bolster SCRE through enhanced real-time monitoring, predictive analytics, automation, and agility. The following section will analyse how various sectors have implemented these technologies to tackle specific difficulties and enhance their SCs.

2.1 Resilience through I4.0 technologies

I4.0, defined by the amalgamation of sophisticated technologies including the Internet of Things (IoT), artificial intelligence (AI), big data analytics (BDA), and automation, is revolutionising SC dynamics. This transition is essential for improving SCRE, defined as the capacity of an SC to anticipate, react to, and recuperate from interruptions.

The implementation of disruptive innovations, including digitalisation and I4.0, enables the creation of novel SC development paradigms, principles, and models. Smart operations and digital SCs arise through the integration of IoT technology and cyber-physical systems (CPS) and smart connected products [10]. According to Ben-Daya, Hassini, and Bahroun [11] along with Hofmann and Rüsch [12], various classifications of digital technologies gained recognition along with their effects on SCs. I4.0 integrates advanced digital, automation, and data-driven technologies to enhance efficiency, flexibility, and innovation in manufacturing and SC operations. BDA started as a concept when Cox and Ellsworth [13] introduced it in 1997 to process large data structures and extract valuable insights [14]. The system uses sensor and machine data to perform predictive maintenance and optimise processes, thereby supporting real-time decisions [15]. CPS combines physical systems with digital processing and networking to monitor operations in real time and enhance smart factory reliability through adaptive control capabilities [16]. Cloud computing (CC) delivers scalable data storage services in addition to processing power and network sharing capabilities across the internet, thus allowing system development to proceed rapidly and smoothly [17]. The cognitive capabilities of human beings can be duplicated by AI through ML combined with neural networks and complex algorithms which enable automatic decision-making as well as quality assessment processes and system optimisation. IoT technology allows devices to connect with sensors while linking machinery through real-time communication systems together with tracking assets and energy consumption methods to provide operational transparency [18]. Block chain technology (BCT) functions as a vital system which delivers secure operation and tamper-evident records and transacts data transparently, thus supporting SC tracking management alongside CPS and automated smart contracts [19]. Additive manufacturing (AM) builds objects layer by layer from digital models, facilitating rapid prototyping, mass customisation, and reduced material waste, transforming traditional manufacturing strategies [20]. Autonomous vehicles (AV) consisting of self-driving cars and automated guided vehicles use autonomous material transport systems to boost safety and operation efficiency while minimising human involvement [21]. The DT system develops exact virtual versions of existing physical entities which let organisations monitor assets and systems in real time and optimise them and their data flows bi-directionally [22]. The simulated environments of VR support safer industrial design prototyping and remote collaboration and immersive training procedures, which make processes both more efficient and cost-effective [23]. The technology of AR allows digital information to blend on top of physical objects thus extending real-time maintenance capabilities while supporting worker training needs and providing operational guidance, which helps workers interpret complicated data in order to minimise mistakes and maximise workplace productivity. Enterprise resource planning (ERP) Systems unite the finance sector together with SC and human resources through a single platform that boosts both operational precision and efficiency of data. The electromagnetic field-based radio frequency identification (RFID) system enables automatic control of inventory and assets while managing quality control standards [23]. Robotics technology performs assembly work and welding operations along with material handling duties which result in advanced precision and accelerated speeds and safer industrial conditions [24]. The integration of control systems with robotics and information technology (IT) produces automation that eliminates human contact and drives consistent safe production results throughout manufacturing lines [25]. Lastly, remote monitoring utilises sensors and communication networks to track equipment performance and condition, supporting proactive maintenance strategies and reducing downtime in critical operations [26].

The adoption of I4.0 technologies enables significant enhancements of SCRE, yet it comes with specific obstacles that need to be addressed. The growing connectivity and data exchange practices within I4.0 generate additional opportunities for cyberattacks that might suspend operations while exposing sensitive information [27]. Protecting against these threats requires strong cybersecurity systems. Kazançoğlu et al. [28] stress the requirement to address security matters for sustainability and resilience when operating in conditions of uncertainty. The integration of several I4.0 technologies including IoT systems, AI capabilities and cloud-based solutions within existing SC systems, becomes both intricate and expensive to implement [29]. The integration processes become more difficult due to interoperability challenges along with previous-generation system limitations. I4.0 technologies, produce large volumes of data that need strong data management and analytics systems [28]. Decision support systems face barriers when they attempt to derive important information from extensive datasets. Organisations need professionals with specific skills when they deploy and operate I4.0 technologies [6]. Current workers must receive enhanced training, and companies need to recruit new staff who excel in AI, and BDA and cybersecurity fields. Tech dependency presents risks that generate new system weaknesses and weak points which threaten network stability [6]. A single disruption in digitally linked SC components spreads rapidly throughout the complete network structure. Small businesses need to allocate sizable funds at the beginning to adopt I4.0 technologies [30]. The process to prove a clear investment return coupled with funding acquisition proves difficult for stakeholders.

The major impact of I4.0 technologies is that it brings more transparency across the SC. IoT enhances the monitoring of commodities through IoT devices; an organisation can monitor the stock, the shipment of the products or any disruptions that may occur. These make decision-making better and response to unplanned events faster, therefore enhancing resilience [31]. BDA and AI can analyse large data to identify trends and predict potential disruptions. Forecasting allows an organisation to assess the potential change in demand or supply as well as constraints in the logistic chain and adjust the strategy and stock and the choice of sources, thus increasing their preparedness for uncertainty [32]. The integration of IoT with data analysis enhances organisational nimbleness in its responsive activities in the face of market dynamism [33]. It enhances decentralised record-keeping and increases transparency along the SC and reduces most duplicities while building confidence among the actors [34]. Analysing resilience in the context of the I4.0, the fuzzy logic model suggests three more measurements: agility, coordination, and innovativeness [35]. Several studies prove how automation and robotics in SC can significantly reduce lead times as well as operation costs. With the help of automation, changes can be made very quickly in demand or supply, ensuring its un-intermittent availability during disruptions. Such flexibility becomes vital in maintaining service delivery and customer satisfaction [36]. Appropriate application of automation and human-centred expertise must be employed to enhance the benefits of the I4.0 technology [33]. Risk management at organisations can be enhanced through the use of modern technologies in more effective tactics. The processing of the information in real-time enables constant monitoring of risks that may pose a threat to an organisation and hence develop ways of handling them as well as resource management. This proactive approach enhances the general SC robustness [37]. I4.0 technologies help to quickly respond to unexpected interruptions and ensure business continuity in unfavourable circumstances [38].

The literature indicates that different businesses implement I4.0 technologies in distinct manners, reflecting sector-specific problems and operational requirements (refer to Table 1). The manufacturing industry is among the most extensively researched sectors regarding the implementation of I4.0 for SCRE enhancement. Technologies including IoT, AI, tracking and traceability, automation, predictive analytics, and simulation, are essential for enhancing operational efficiency and resilience. Research conducted by Ralston and Blackhurst [6], Lopes de Sousa Jabbour [26], Nakandala et al. [39], Tian et al. [40], and Dey et al. [41] emphasises the significance of AI, IoT, BDA, CPS, and ERP in enhancing SCRE. Real-time decision-making arises from DT together with remote monitoring systems and sensors to cut down downtimes while boosting the agility of SCs. The automobile industry utilises BDA, CPSs, the IoT, AI, and BCT to improve SCRE through predictive maintenance, enhanced visibility, and real-time tracking. Spieske and Birkel [32] analyse essential applications of BDA, AM, CPS, CC, IoT, and AI to sustain the effectiveness of automotive SC risk management and disruption control. The healthcare sector emphasises digitalisation, automation, and machine learning (ML) to maintain robust SCs, especially during critical events such as pandemics or shortages of medical supplies. According to Rehman and Ali [25], healthcare SCRE benefits extensively from digitalisation together with ML and automation. The food beverage and pharmaceutical industry give top priority to IoT, ML, BCT and BDA technologies for ensuring traceability quality control and regulatory compliance. Both Qader et al. [31] and Tortorella et al. [42] evaluated how IoT, ML, BCT, RFID, AI, and robotics assist food and pharmaceutical SCs to strengthen their resilience. The oil and gas sector relies on I4.0 technology elements, including AI, and BDA, and IoT and BCT, to address regulatory issues while enhancing both SC efficiency and logistics operations and operational risk management. Jain et al. [43] explore how I4.0 technologies, when utilised alongside SCRE, improve industrial operational efficiency in this field. Operating the LNG sector requires combining AI technology with both IoT and BDA systems and CPS and BCT systems that help with unpredictable operations and disruption management. The study conducted by Al-Khatib et al. [44] shows that using AI with BCT creates enhanced resistance for LNG SCs. Digital transformation functions as an essential instrument for sports industries to enhance their security and reliability standards in emerging markets. Wang et al. [45] outlined the ways digital transformation strengthens SCRE properties within sports industry operations. The shipbuilding industry applies augmented reality (AR) along with AM to optimize production processes and minimize lead times thus improving SCRE. Centobelli et al. [46] highlights how these technologies contribute to resilience in shipbuilding.

Table 1. Literature on the impact of I4.0 technology on SCRE

S/N	Reference	SC Resilience	Industry/Sector	I4.0 Technology
1	Ivanov et al. [37]	✓	–	BDA, AM, Tracking and tracing technologies, CPS, CC
2	Belhadi et al. [47]	✓	Automobile and Airline	BDA
3	Lohmer et al. [48]	✓	–	BCT
4	Ralston and Blackhurst [6]	✓	Manufacturing	I4.0
5	Spieske and Birkel [32]	✓	Automotive	BDA, AM, CPS, CC, IoT, BCT, AI
6	Dev et al. [23]	✓	–	Simulation, RFID, ERP, CPS, VR, IoT, Sensors
7	Kumar et al. [49]	✓	–	Smart Warehousing
8	Bag et al. [50]	✓	Healthcare	BDA
9	Peng et al. [51]	✓	Manufacturing	IoT
10	Qader et al. [31]	✓	Food, beverage, and pharmaceutical industries	IoT, ML, BCT, BDA
11	Gupta et al. [52]	✓	–	BDA, AM
12	Rehman and Ali [25]	✓	Healthcare	Digitalization, ML, Automation
13	Tortorella et al. [30]	✓	–	ERP, BDA, RFID, IoT, Sensors, CC, CPS, BCT, AR, VR, AM, Digital twin, ML
14	Hsu et al. [53]	✓	Manufacturing	IT, digitalization, BDA
15	Chatterjee et al. [54]	✓	–	AI, BCT, IoT
16	Naz et al. [55]	✓	–	AI
17	Lopes de Sousa Jabbour et al. [26]	✓	Manufacturing	Digital Automation, Remote Monitoring, Simulation, IoT, BDA

(Continued)

Table 1. Literature on the impact of I4.0 technology on SCRE *(Continued)*

S/N	Reference	SC Resilience	Industry/Sector	I4.0 Technology
18	Centobelli et a. [46]	✓	Shipbuilding	AR, AM
19	Spieske et al. [9]	✓	–	BDA, AM, IoT, BCT, AI, DT, AV, Remote working, Digital capabilities, Data aggregation
20	Huang et al. [36]	✓	–	AI, AR, AV, BCT, BDA, Business Intelligence, CC, ERP, IoT, RFID, Robotics, Sensor, Simulation, VR, 3D printing
21	Frederico et al. [56]	✓	–	IoT, BDA, CC and Cyber Security Systems, CPS
22	Alvarenga et al. [57]	✓	–	IoT, CC, BDA, DT, BCT
23	Nakandala et al. [39]	✓	Manufacturing	Identification and Traceability, Sensors, Actuators, ERP, AI, CC, BDA, CPS
24	Senna et al. [58]	✓	Healthcare	RFID, BCT
25	Razak et al. [59]	✓	–	CPS, 3D printing, Robotics, AI, Aerial Vehicles, BDA, BCT, IoT, AR
26	Manikas et al. [60]	✓	Logistics	BDA
27	Calza et al. [61]	✓	Manufacturing	IoT, BDA, AI, AM, Robotics
28	Marinagi et al. [62]	✓	–	IoT, CPS, AR, CC, BDA, AI, DT, BCT, robotics and AM
29	Tian et al. [40]	✓	Manufacturing	IoT, AI
30	Al-Khatib et al. [44]	✓	liquefied natural gas (LNG) SC	AI, IoT, BDA, CPS, BCT
31	Riaz et al. [63]	✓	–	I4.0
32	Wang et al. [45]	✓	Sports industry	Digitalization
33	Tortorella et al. [42]	✓	Food SC	ERP, RFID, IoT, Sensors, CC, Robotics, Blockchain, AR, VR, ML, AI
34	Sharma et al. [64]	✓	–	ML
35	Jain et al. [43]	✓	Oil and gas	I4.0
36	Piprani et al. [65]	✓	Manufacturing	IoT, BCT, BDA, ML
37	Madrid-Guijarro et al. [38]	✓	Manufacturing	BDA, Predictive analytics, CC, Automation
38	Dey et al. [41]	✓	Manufacturing	AI
39	Reyes et al. [66]	✓	Footwear sector	CC
40	Guo and Mantravadi [67]	✓	–	DT
41	Li et al. [68]	✓	Construction	Digitalization
42	Belhadi et al. [69]	✓	Fast moving consumer goods, chemical industry, Automobile, Electronic industry, Mining, Pharmaceutical	AI
43	Lei et al. [70]	✓	Automotive	Simulation
44	An et al. [71]	✓	Apparel	IoT
45	Ghobakhloo et al. [72]	✓	–	AM, AR, VR, Robotics, AI, BCT, CC, BDA, DT, IoT, CPS, Cyber security

Note: Big data analytics (BDA), cyber-physical systems (CPS), cloud computing (CC), artificial intelligence (AI), internet of things (IoT), machine learning (ML), block chain (BCT), augmented reality (AR), additive manufacturing (AM), autonomous vehicle (AV), digital twin (DT), virtual reality (VR), enterprise resource planning (ERP), radio frequency identification (RFID).

Numerous I4.0 technologies are recognised as essential facilitators of SCRE: BDA and AI are frequently employed for predictive analytics, risk management, and decision-making [23], [37], [47], [52]. They also found out that the level of BCT is highly appreciated due to its ability to ensure transparency and traceability in the SC more especially in manufacturing and logistics [23], [48]. The IoT and CPS play a critical role in real-time monitoring and control, automation and improvement of system performance [25], [32], [36]. ML is used for its ability to predict in relation to disturbances and to enhance SC, adaptability [23], [30]. AV and DT technology are gradually being identified in some industries, such as the shipbuilding and automobile industries, to emulate SC conditions and enhance the decision-making unit.

2.2 Industry-specific adoption of resilience technologies

BDA, IoT and automation have been widely adopted by manufacturing industries to reduce disruption of the SC and to improve SC flexibility of I4.0. Ralston and Blackhurst [6] discuss how I4.0 affects capability and resilience issues, while de Sousa Jabbour et al. [26] explain that the integration of automation and BDA is critical to SC improvement. Owing to the COVID-19 impact, the automotive industry relied heavily on CPS, CC, and simulation to increase its robustness [9]. In healthcare, digitalisation, AI, and automation are essential for enhancing the agility and responsiveness of SCs to external disruptions [25]. The incorporation of I4.0 technologies in healthcare SCs has proven crucial for better resource management during crises. The food, beverage, and pharmaceutical industries have implemented IoT, ML, and BDA to augment traceability, anticipate interruptions, and enhance real-time monitoring. Dev et al. [23] and Frederico et al. [56] emphasise the enhancement of resilience through these technologies, particularly in mitigating SC risks amid the pandemic. AR and AM are progressively utilised in the shipbuilding industry to enhance the digitalisation of SC processes [46]. Piprani et al. [65] emphasise the utilisation of IoT, BCT, and ML in the oil and gas sector to bolster SCRE through improved visibility and the management of intricate logistics systems.

Industries are concentrating on resilience techniques that utilise real-time data, predictive modelling, and automation to alleviate SC interruptions. The COVID-19 pandemic has expedited the implementation of I4.0 technology to address unpredictability and enhance SCRE, [9], [30], [36]. Comparisons across industries indicate differing degrees of digital transformation based on each industry's preparedness and maturity [39], [57].

3 METHODOLOGY

Figure 1 delineates a conceptual framework for evaluating the influence of I4.0 technologies on SCRE. The method commences with a literature review that finds 25 I4.0 technologies, albeit some of these technologies are redundant. The subsequent I4.0 technologies have been eliminated to refine the list: ML and predictive analytics are excluded as they constitute a subset of AI. Digital capacity is eliminated because of its extensive scope and overlap with digitalisation, which denotes the overarching shift. Furthermore, digitalisation is excluded, as it results from the use of numerous I4.0 technologies such as CC, IoT, automation, and BDA. The term "tracking and tracing technologies" is eliminated, as RFID exemplifies such technologies. Simulation is omitted as DT encompasses simulation and signifies a more advanced, specialised application. Data aggregation is excluded, as it constitutes a subset of BDA that encompasses data aggregation inside the process. Sensors and actuators, integral components of CPS and the IoT, have been eliminated. Remote monitoring is categorised within the IoT or CC, since it generally entails utilising IoT devices to gather real-time data from physical assets, processes, or environments. The data is subsequently transported across networks, frequently utilising CC, for monitoring and analysis. Superfluous I4.0 technologies are eliminated, yielding a streamlined list of I4.0 technologies affecting SCRE. The SCRE network design requirements encompass characteristics such as flow complexity, node complexity, SC density, and node criticality (refer to Table 2). The best worst method (BWM) is employed to evaluate these criteria, subsequently utilising the measurement of alternatives and ranking according to compromise solution (MARCOS) technique to rank the discovered I4.0 technologies according to their influence on SCRE. The methodology offers a systematic method for assessing the significance of I4.0 technologies in bolstering SCRE, underpinned by quantitative decision-making methodologies.

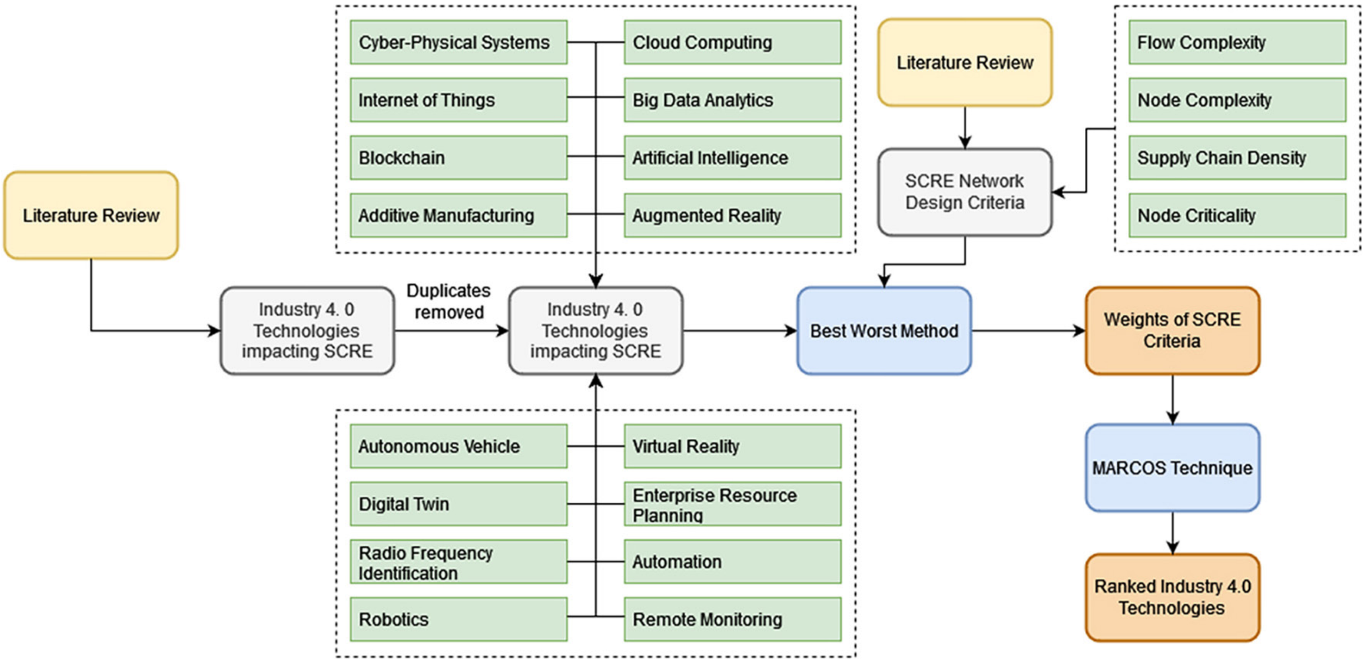

Fig. 1. Research methodology

Table 2. SCRE design criteria

S/N	SCRE Design Criteria	Reference
1	Flow Complexity	Cardoso et al. [73]
2	Node Complexity	Cardoso et al. [73]
3	Node Criticality	Adenso-Diaz et al. [74], Kumar et al. [75]
4	SC Density	Kumar et al. [75], Mikhail et al. [76]

4 RESULTS AND DISCUSSION

Table 3 displays the outcomes of employing the BWM to ascertain the weights of different criteria affecting SCRE, based on inputs from five decision-makers, which include two industry experts and three academic experts with 5–7 years of experience. BWM is a decision-making technique that systematically identifies the best and worst criteria, followed by pairwise comparisons to determine their relative significance. The criteria assessed are presented in Table 2. The analysis indicated that node criticality carries the highest weight (0.6560), highlighting its crucial role in improving SCRE, whereas SC density was assigned the lowest weight (0.0709), suggesting its reduced importance. The consistency ratio of 0.0714, significantly below the acceptable threshold, indicates a high level of reliability and consistency in the experts' judgements. The BWM accurately reflected the priorities of the experts, emphasising the essential function of node robustness in enhancing SCRE.

Table 3. BWM method result

SCRE Design Criteria	Flow Complexity	Node Complexity	Node Criticality	SC Density
Weights	0.14893617	0.12411348	0.65602837	0.07092199

The weights of criteria were obtained after the BWM was employed to rank various I4.0 technologies using the MARCOS method (refer to Table 4). Four experts, each with six to ten years of experience, participated in the assessment: two of the participants are from the academic field and the other two from the industrial sector. The results seem to suggest that AI has the highest value, with a normalised weight of 0.1115, seconded by BDA with normalised weight of 0.1001. ERP and AM had the lowest scores, 0.0253 and 0.0127, respectively in terms of weightage. This ranking is the sum of the assessment of all the specialists, who considered the score such as the potential significance and applicability of these technologies to SCRE.

Table 4. Rank of I4.0 technology

S/N	I4.0 Technology	Normalized Weight	Rank
1	BDA	0.1001	2
2	Cyber-Physical Systems	0.0791	6
3	Cloud Computing	0.0840	5
4	AI	0.1115	1
5	IoT	0.0859	3
6	Blockchain	0.0853	4
7	Augmented Reality	0.0396	13
8	Additive Manufacturing	0.0127	16
9	Autonomous Vehicle	0.0511	12
10	Digital Twin	0.0677	7
11	Virtual Reality	0.0297	14
12	Enterprise Resource Planning	0.0253	15
13	Radio Frequency Identification	0.0526	11
14	Robotics	0.0615	8
15	Automation	0.0609	9
16	Remote Monitoring	0.0531	10

The findings outlined above hold considerable relevance for policymakers aiming to utilise I4.0 technologies to improve SCRE. The study identifies AI as the most significant I4.0 technology for enhancing SCRE. Policymakers ought to promote AI adoption by providing incentives, funding research and development, and facilitating the cultivation of AI-specific skills and talent. This may include tax incentives, grants, and subsidies for enterprises investing in AI-enhanced SC solutions. Facilitating educational institutions and training programs to prepare the workforce with essential AI competencies. Establishing frameworks for secure and ethical experimentation with AI technologies in SCs.

The study highlights the significance of node criticality in enhancing SCRE. Policymakers can enhance node management by improving the infrastructure of critical nodes, which may include ports, transportation hubs, and communication networks. Promoting the diversification of supplier bases among businesses to mitigate dependence on singular critical nodes.

Policymakers may promote data-driven decision-making by establishing standards for data collection and exchange in SCs. Establishing effective cybersecurity policies to safeguard sensitive SC information. Kanti et al. [77] emphasises the significance of SC risk management, particularly in relation to cybersecurity. Facilitating the establishment of essential data infrastructure, including CC and high-speed internet connectivity.

Collaboration across various sectors and industries is essential for enhancing SCRE. Policymakers can promote collaboration by fostering partnerships between industry and research institutions to create and apply innovative solutions. Encouraging cooperation between governmental entities and private enterprises to tackle shared SC issues. Collaborating with international partners to establish coordinated strategies for enhancing SCRE on a global scale. Naz et al. [55] highlight the influence of AI on SC performance.

Policymakers can foster a culture of resilience in businesses through the following measures: Informing businesses regarding the significance of SCRE and the advantages of implementing I4.0 technologies. Promoting the exchange of best practices and insights among organisations. Riad et al. [78] present a framework for the implementation of AI in SCs.

Implementing these policy recommendations allows governments to foster an environment where businesses can fully utilise I4.0 technologies to improve SCRE, ensure economic stability, and promote sustainable growth.

5 CONCLUSION

The framework has been developed to outline the procedure of assessing the effect of I4.0 technology on SCRE enhancement. The process involves a systematic search for relevant literature, followed by a careful fine-tuning of the technologies in the context of relevance redundancy. The other technologies are then evaluated based on other critical SCRE network design features such as node importance and SC connectivity density using the integrated BWM and MARCOS approach. The outlined multi-phase method provides a solid and quantifiable roadmap for understanding the effect of I4.0 technologies in increasing SC robustness. From the BWM, it was established that node criticality is critical, while SC density is less so based on the expert input. After that, the MARCOS technique identified AI as the most impactful I4.0 technology on SCRE, followed by BDA and IoT. In light of these insights, node robustness emerges as a critical factor in building SCRE, and the role of AI solutions as a means for achieving such resilience is affirmed.

The research is mainly carried out through the evaluation of opinions from key stakeholders. Despite the fact that there is a limitation in the number of specialists and their specific background there might be bias. I4.0 is constantly evolving. The new innovations emerge rapidly, and this may alter the importance and positions of the investigated technologies. The research may be restricted to a given geographical area. Location influences both the SC dynamics and the use of technology, thus affecting SCRE. Reviewing the Impacts of I4.0 technologies on SCRE might provide valuable information concerning their continuous effectiveness. Real life examples of how these technologies have been implemented for SCRE in firms can give practical examples and support the framework. More detailed research regarding the influence of other factors like organisational culture and governmental legislation in the interaction with I4.0 technology to SCRE can be beneficial. Future studies may focus on developing dynamic simulation models which analyse disruption evolution alongside I4.0 enabled adaptive SC responses. Future research can analyse how SCRE strategies might impact sustainability goals while assessing the related economic trade-offs. I4.0-technologies improve both components; however, some resilience measures generate unintended negative impacts on the environment along with social aspects. Further research can focus on how resilience and sustainability relate to each other through comparative analysis followed by the development of integrated resilience and sustainability approaches. The current research about SCRE employs generalised investigation methods. Future investigations may concentrate on examining industry-specific circumstances such as healthcare and manufacturing since they provide chances to identify particular challenges when implementing I4.0 technologies for enhancing resilience.

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