**Can Industry 5.0 develop a resilient supply chain? An integrated decision-making approach by analyzing I5.0 CSFs**

Rahul Sindhwani

Operations Management Area

Indian Institute of Management Sambalpur, Odisha, India (rahul.sindhwani2006@gmail.com)

Abhishek Behl*

Management Development Institute, Gurgaon, India; (abhishekbehl27@gmail.com)

Ramandeep Singh

Amity University Uttar Pradesh, Noida, India (rs.ramandeepsingh999@gmail.com)

Sushma Kumari

Hull University Business School, University of Hull (S.Kumari@hull.ac.uk)

*Corresponding Author

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# Can Industry 5.0 develop a resilient supply chain? An integrated decision-making approach by analyzing I5.0 CSFs

## Abstract

Advances in science and technology act as the gatekeepers of a sustainable future where a stable environment helps generate the power for innovation. Supply chains are the messengers of this euphoric future. However, when the messengers and the gatekeepers are not in sync, the flow of information is bound to stop and bring about a chaotic turn of events, the repercussions of which can be felt through the years. The same was the case with the COVID-19 pandemic, where the lack of man-machine collaboration in Industry 4.0 and the inability of firms to advance their supply chains technologically left them exposed and vulnerable to the disruptions created by the pandemic. It was an eye-opener for companies worldwide as the supply chains collapsed and production reached a standstill. Thus, a stance arises to re-evaluate the resilience capabilities of the supply chains and rethink the priorities for achieving sustainable and resilient supply chain practices. We also suggest injecting industry 5.0 technologies to meet the re-assessed priorities. For this, we have identified the criteria and CSFs of supply chain resilience using the PRISMA 2020 statement and subsequently analyzed them using PF-AHP (for finding criteria weights), m-TISM (to interpret the interrelationships of the CSFs), PF-CoCoSo (to rank the CSFs) and sensitivity analysis (to check the robustness). The results suggest cost-effectiveness as the top weighted criteria and disruption awareness as the highest priority CSF for achieving supply chain resilience.

**Keywords:** Supply chain resilience, Industry 5.0, Critical success factors, PF-AHP, m-TISM, PF-CoCoSo, Sensitivity analysis

## 1. Introduction

The term supply chain is often used for describing the flow of products, services, or information between three or more entities/members (Mentzer et al., 2001), where each member involved has to play a certain role and fulfill their responsibility to meet and satisfy the end needs (Hugos, 2018). One of the key tools available to an organization participating in a supply chain is supply chain management (SCM), which allows for the business processes of the involved members to be effectively integrated to reduce the costs associated while improving quality and promoting innovation at the same time (Crook and Combs, 2007). Maintaining a healthy supply chain through good customer relations and purchasing practices allows firms to improve their market performance with effective SCM strategies (Tan et al., 1998). To better the operations of the supply chains, many executives implemented various measures to decrease the costs while improving profits; however, these measures proved to be more disruptive than productive in today's turbulent economy (Tang, 2006).

A supply chain constantly faces myriad risks, ranging from natural disasters and economic crises to geopolitical tensions and technological uncertainties, making it one of the key areas for companies to focus on to reduce disruptions and maintain continuous operations (Karl et al., 2018). To overcome market disruptions and increase their chain’s responsiveness, firms started to look for opportunities to collaborate with other members of the chain and use their combined resources to efficiently execute their operations (Hudnurkar et al., 2014). A more collaborative supply chain not only promotes an elevated level of visibility and flexibility but also ensures reduced overall lead times, enabling better performance and uninterrupted operations management (Scholten and Schilder, 2015). Even though firms have been successful in mitigating disruptions to a certain extent, they have not yet been completely successful in making themselves capable of dealing with the shocks and the aftermaths of the disruptions, the most recent example of which is the COVID-19 pandemic. The coronavirus outbreak has affected supply chains worldwide, bringing complex challenges that have disrupted operations globally (Queiroz et al., 2022). Dire situations, such as the ones created by the pandemic often leave businesses and people heavily reliant on the government for their health and safety (Tremblay et al., 2023), which can have a hefty price in the form of continuity of services. A simple example of this can be seen when the precautionary measures enforced by the governments, such as the nationwide curfews, social distancing practices, and emergency lockdowns, which certainly helped in decelerating the virus outbreak, created new problems in other areas such as the downtrend of travel and tourism industry with people losing their jobs or having their incomes cut down (Choudrie et al., 2021).

Supply chain resilience is not a new concept and it can be pinpointed towards the end of the 1950s with the introduction of the term bullwhip effect, concentrating on the demand risks. It was later expanded to include more risks, such as supply and control and risks related to globalization, supplier reduction, etc. (Remko, 2020). A supply chain is said to be resilient when it can anticipate disturbances, resist their spread, and recover via effective reactive strategies to restore itself to its original state (Kamalahmadi and Parast, 2016). Even though there are a lot of studies on the topic, resiliency in the supply chain still eludes us. The current research attempts to help achieve resilience by analyzing the critical success factors (CSFs) of supply chain resilience and attaining these CSFs through the latest technologies available by suggesting the convergence of industry 5.0 and supply chain resilience.

Industry 5.0 (I5.0) refers to the fifth and the latest revolution in the long line of industrial revolutions, the first of which can be tracked down to the 1780s (Nahavandi, 2019). I5.0 has two visions associated with it, the first being it aims to make collaborative operating conditions between humans and machines focused on advancements in robotics and artificial intelligence (AI) (Demir et al., 2019). The other theme associated with I5.0 is that it was introduced due to the limitations of industry 4.0 in linking with the concepts of social fairness and sustainability (Xu et al., 2021). Industry 4.0, aimed at digitization of manufacturing business through information technologies (Han et al., 2021), is deeply linked with the evolution of information technologies, and the convergence of information technologies leads to the path of I5.0 through the advancement of information systems (Martynov et al., 2019). I5.0 focuses on human centricity to empower workers through advanced IT technologies, AI, augmented reality, etc., and become a sustainable source of development (Akundi et al., 2022). I5.0, when applied to SCM, can help us achieve better integration and hyper-customization, enabling us to reduce the risks associated and form strategic alliances to increase supply chain efficiency and profits (Humayun, 2021). I5.0 stands as the vanguard of the Industrial Revolution, representing a profound leap forward from the foundational principles of I4.0. While the advent of I4.0 marked a significant turning point by ushering advanced technologies into industrial processes, I5.0 carries this integration to an unprecedented level. At its core, I5.0 underscores the paramount importance of fostering a symbiotic relationship between cutting-edge technologies and the human workforce. It champions a visionary concept known as human-machine collaboration, wherein a sophisticated tapestry of technological marvels, including artificial intelligence (AI), the Internet of Things (IoT), big data analytics, and augmented reality, harmoniously converge with human expertise. This synergy fuels innovation, boosts productivity, and, perhaps most notably, enacts as the bedrock for enhancing supply chain resilience. Our primary focus revolves around illuminating the pivotal role of I5.0 technologies in propelling supply chain resilience to new heights. By embarking on this exploration, we provide a crystalline perspective on how these technologies constitute the very essence of the shift from I4.0 to I5.0, reshaping the landscape of modern supply chain management. With reference to the same, the authors have scoped to find the enablers and technologies of I5.0 that can help achieve supply chain resilience. Quality articles pertaining to I5.0 were used to find the technologies such as big data analytics (BDA), internet of things (IoT), artificial intelligence (AI), digital twin, advanced simulation, cyber-physical systems (CPS), 5G-6G and beyond, etc. that can help achieve resilience in supply chains.

Supply chain resilience has often been viewed from a research point of view, and a lot of research has been done previously to help industries attain the necessary resilience by means of evaluation of its enablers, barriers, and CSFs. However, the fact that global supply chains are unprepared for situations such as the COVID-19 pandemic brings light to the lack of resilience and motivates us to re-evaluate our preparedness and accordingly re-sensitize the supply chains by using the latest technologies. In this work, the CSFs of supply chain resilience are analyzed, and the authors suggest achieving them by injecting the supply chains with I5.0 technologies, thus making the supply chains resilient. Identifying and analyzing the criteria and CSFs of supply chain resilience will allow industries to check the priorities for realizing resilient supply chain practices. Along with the analysis of the CSFs of supply chain resilience, the study also contributes towards the use of I5.0 technologies to achieve the said CSFs, thus directly influencing the resilience of supply chains using the latest technologies and providing the industries and managers with plausible solutions that can create great impacts in a shorter amount of time. Through the work, the authors will address the following research questions (RQ):

RQ-1: What criteria and critical success factors are essential for achieving supply chain resilience, considering changing market conditions and emerging risks?

Identifying the CSFs of any particular concept allows the industries to easily organize themselves in certain ways that make them readily adapt and successfully integrate the concept into their operations. Thus, our initial step was to identify the criteria as well as critical success factors of supply chain resilience. To answer the above RQ, the authors adopted the PRISMA 2020 approach, and only the quality articles that satisfied all the constraints discussed in section 2.1 were selected. Furthermore, the identified CSFs were validated using the Delphi method by providing a research questionnaire to the experts who collected their inputs, and only the accepted CSFs were considered. After successfully identifying and selecting the criteria and CSFs, there is a need to judge their importance concerning one another, and here becomes apparent our next RQ.

RQ-2: How can the criteria be systematically weighted to reflect their relative importance and the CSFs be prioritized to help industries achieve supply chain resilience?

The identification of the CSFs does provide us with the necessary measures that should be taken to achieve resilience in supply chains; however, it does not empower us to recognize the optimum path that can be taken. Ranking and prioritizing the CSFs will help us understand their impact levels, which can help us become resilient in the least possible steps. To answer the RQ-2, we propose a four-phase hybrid methodology. First, the authors will evaluate the weightage of the criteria selected using Pythagorean Fuzzy AHP. Secondly, we will use the m-TISM approach clubbed with MICMAC analysis to determine the driving and dependent CSFs; only those with higher driving powers will be further analyzed. In the third phase, the weights calculated from PF-AHP will be used in Pythagorean Fuzzy CoCoSo to rank the final CSFs obtained after m-TISM and MICMAC analysis. Lastly, sensitivity analysis will be employed to check the robustness of the results. In this way, the authors will implement a four-stage hybrid methodology to create a framework for the industries to achieve resilient supply chains.

In the recent years, supply chains globally have been plagued with unprecedented challenges which have brought along with them significant disruptions, particularly seen in case of the COVID-19 pandemic. These disruptions have highlighted for the industries, the immediate need of transforming their supply chains and adopting the concepts of robustness and resilience. The current study is focused on capturing the essence of this transformative journey which underlines the shift in the contemporary business strategies and addresses the necessity for supply chains to evolve in the face of volatile global landscape. The traditional approach, driven towards cost-efficiency and lean practices, has been rendered unfruitful against these unpredictable challenges, making it essential for industries to recognize how they can evolve their supply chains into resilient entities that are capable of predicting, persevering and prospering through these disruptions. The current study explores this transformational journey by identifying and prioritizing the criteria and the critical success factors (CSFs) integral to supply chain resilience.

Moreover, we delve into the pivotal role of Industry 5.0 (I5.0) technologies in catalyzing this transformation, illuminating the path for organizations to fortify their supply chains while harnessing the potential of cutting-edge technologies. A few notable contributions made by the study are identifying and analyzing the criteria and CSFs of supply chain resilience, cost-effectiveness, and technological advancement, which were the two highest weighted criteria. Disruption awareness was the most important and highly ranked CSF; based on the weightage and ranking, we also provided key recommendations to industries for influencing supply chain resilience with the help of I5.0 technologies and discussed the study's contributions toward theoretical implications. To conduct a proper analysis of the criteria and CSFs identified through a scoping literature search, the authors took the help of robust multi-criteria decision-making (MCDM) tools such as the Delphi technique for validation of the identified CSFs, PF-AHP for calculation of the criteria weights, m-TISM and MICMAC analysis for developing hierarchical model to study and interpret the relationships and calculation of dependence and driving power of the CSFs, PF-CoCoSo for ranking the CSFs in priority order and finally sensitivity analysis for checking the robustness of the framework. Our research aligns with the growing consensus in the literature, emphasizing the essential role of factors like awareness of disruptions, establishing redundancy, and fostering agility in attaining supply chain resilience. These findings resonate with research by Yu et al. (2019), who also underscored the importance of disruption orientation and alertness in supply chain resilience.

Furthermore, our prioritization of these CSFs echoes the insights of Fontana et al. (2023), who emphasized the significance of building redundancy through inventory management and supplier relationships. By explicitly drawing these parallels and distinctions, we aim to provide a comprehensive view of how our study contributes to and enriches the ongoing discourse on supply chain resilience. Further, existing literature reveals that while previous researchers have explored various aspects of supply chain resilience and the role of advanced technologies, our research provides distinct insights. Notably, our prioritization of CSFs and criteria, as determined by a hybrid methodology combining PF-AHP, m-TISM, and PF-CoCoSo, sheds new light on the specific CSFs which are vital for achieving supply chain resilience in the context of Industry 5.0. By contrasting our results with those of prior studies, we emphasize the unique contributions of our research and underscore the relevance of our findings in the current supply chain management landscape.

The structure of the research paper is as follows: Section 2 will discuss the literature review showcasing the study selection process and validations of the identified CSFs. Section 3 provides the detailed methodology adopted by the authors, along with the results. Section 4 discusses the authors' results and recommendations for using I5.0 technologies to target the priority CSFs. Section 5 states the work's conclusion, limitations, and future recommendations.

## 2. Literature Review

Industry 5.0 looks to increase the involvement of humans by integrating human intelligence and automation in machines to develop an enhanced collaborative work environment (Longo et al., 2020). Contrary to its technology-centered predecessor, I5.0 takes a human-centric approach and seeks to make processes more sustainable and resilient (Madsen and Berg, 2021). I5.0 looks to enter an age of mass customization where robots and human intelligence can be clubbed together to allow industries to customize their products and tailor them to meet every customer's expectations (Pathak et al., 2019). Using artificial intelligence systems to improve performance and reliability by forming collaborative alliances with humans can also help dissipate the longstanding fear in society regarding the disappearance of human workers' needs with the advancement of technology (Lu et al., 2022).

The last few years have been a time of great turmoil for people, governments, and industries all over the globe. The COVID-19 pandemic had already severely disrupted operations on a global scale (Ozdemir et al., 2022), and the added weight of the Russia-Ukraine conflict proved to be much more than what we bargained for (Orhan, 2022). These and other looming threats, such as China's recent real estate crisis (Cheng, 2022), burden our already fragile supply chains. The supply chain disruptions are evidence of the need for resilience in today's world. Resilience is a multidisciplinary concept and can be described as the ability to maintain or regain original condition in the face of adversities. Similarly, the term supply chain resilience has been defined as the ability of a supply chain to actively handle any disruptions by adapting to respond, recover, and maintain continuous operations at the desired level of control (Ponomarov and Holcomb, 2009).

The supply chain members pivot on one another for resources and information, which further leads to uncertainty and risks (Mondal and Samaddar, 2021). The COVID-19 pandemic has showcased how easily the supply chain networks can be broken down, helping us realize the inefficiency of I4.0 in achieving resilience. On the other hand, the often-overlooked human resources were quick in judging the nature of the threat and in coming up with effective procedures using their knowledge, experience, and abilities to power the technology available to them in generating a state of resilience (Zizic et al., 2022). The integration of human skills with the advancement in technology, especially the integration of the internet with every activity, has had a powerful influence on the supply chain and logistics sector in overcoming the pandemic, making I5.0 the need of the hour to meet the customer demand on time and at minimal cost (Bhargava et al., 2022).

This section will showcase the current literature on supply chain resiliency, the effects of COVID-19 on supply chains, the correlation between Industry 5.0 and resilience in supply chains, the definitions of the identified criteria and critical success factors, and the research highlights.

*2.1 Study selection process:*

The authors performed a systematic review by searching extensively for studies and articles on supply chain resiliency on Scopus. To achieve the complete and transparent reporting of the work undertaken, the study follows the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement.

The PRISMA group developed and put forward the PRISMA guidelines in 2009 (Moher et al., 2009). The guidelines were recently updated to cover the latest advances in systematic review methodologies and terminologies and are now identified as the PRISMA 2020 statement (Page et al., 2020).

*2.1.1 Study identification process*

For conducting the literature review, the authors searched Scopus and Web of Science databases by using keywords such as 'Supply chain' OR 'Resiliency' OR 'Enablers' OR 'Success factors' OR 'Sustainable supply chain' in combination with terms such as 'Internet of things,' 'Cloud computing', 'Artificial Intelligence,' 'Digital twin,' 'Additive Manufacturing,' 'Cloud computing' etc., we found around 1,456 papers from all three databases and three records from other sources such as websites, online sources, etc. The search criteria were limited to only English articles between 2016 and October 2022. The articles were checked for duplicity by exporting all the articles in CSV Excel format and the relevant information. The excel file was then sorted, and duplicate entries were identified. A total of 793 records were identified as duplicates and removed. Furthermore, the authors must mention that 02 external websites or organizations were consulted in the current study.

*2.1.2 Screening process*

A total of 663 studies were screened carefully by the authors to identify and include only the quality and relevant articles. After screening the titles and the abstracts, 432 studies were excluded as they were irrelevant to the research objective. The remaining 231 records were retrieved and then studied thoroughly to assess them for eligibility. In this step, a total of 174 articles were excluded from the study for a variety of reasons: outcome not relevant (n = 78), not aligned with the research (n = 55), and lack of data (n = 11).

After reviewing 60 studies, the authors identified four criteria and 10 CSFs for a resilient supply chain. Figure 1 shows the entire selection process. Tables 2 and 3 show experts' validation of the criteria and CSFs. The authors validated the identified CSFs using the Delphi approach to eliminate bias from the judgment and selection phase. Next, we explain validation.

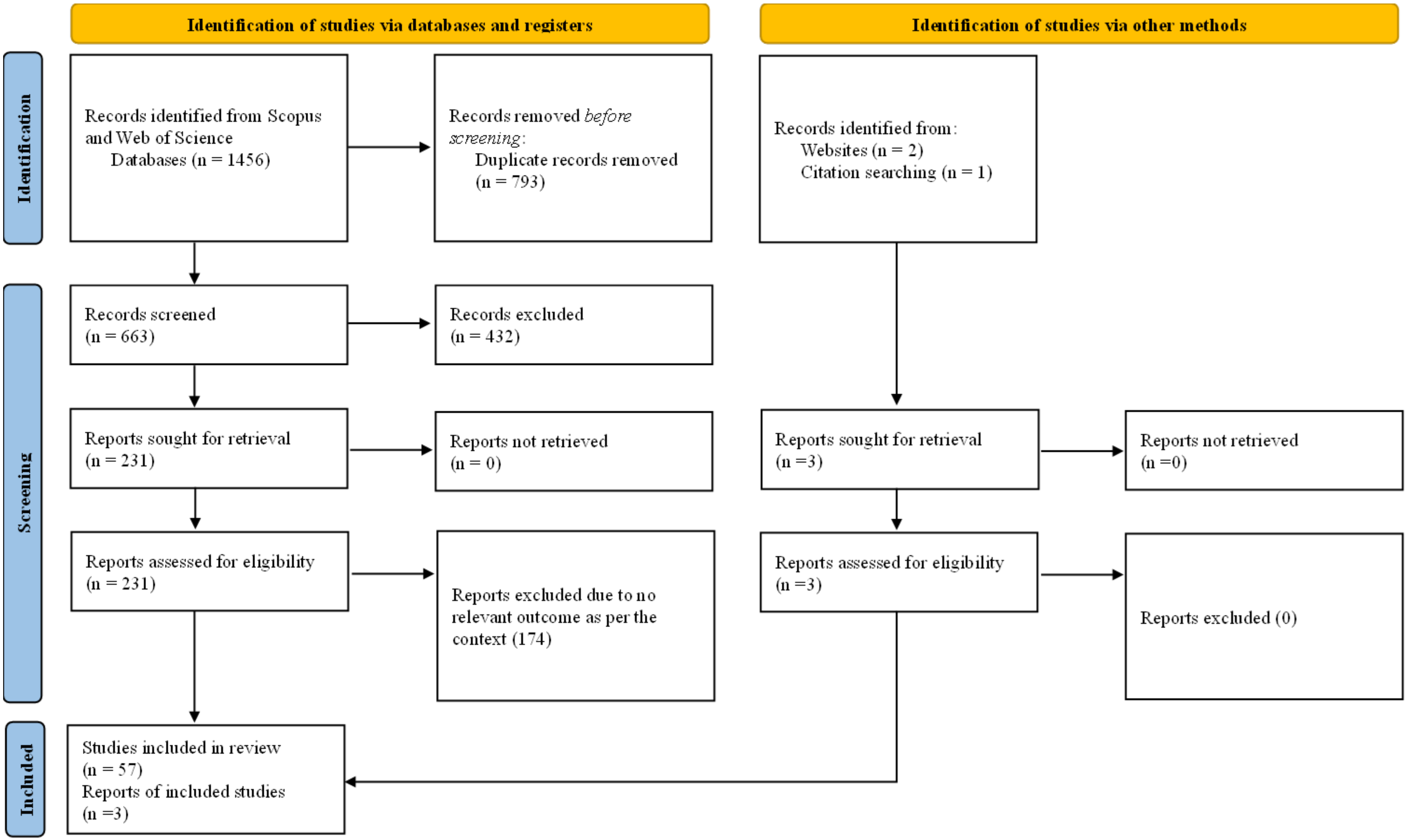



**Figure 1:** Identification of studies using PRISMA guidelines

*2.2 Validation of CSFs identified*

The Delphi method, collects expert inputs for decision-making and forecasting (Landeta, 2006). A group of people uses a structured communication process to solve complex problems using the Delphi technique (Linstone and Turoff, 1975). The Delphi method was designed to be flexible and only require qualified experts (Bouaynaya, 2020). The authors chose seven relevant experts from various industries using purposive sampling to meet this requirement. The number of experts was limited to seven to improve quality and reduce quantity. Generally, five experts are considered enough, as any additional reviewers will not affect the quality of the study greatly (Dumas et al., 1995). The seven experts chosen for this study are from different domains and share an average of more than 12 years of experience among them. The authors consider seven experts to be a satisfactory number for experts to be included in this type of study. The details of the selected experts are provided in Table 1.

**Table 1.** Details of the experts

| Expert No. | Domain | Qualification | Years of Experience |
|---|---|---|---|
| Expert-1 | Supply Chain Management | PhD | 12 |
| Expert -2 | Retail | M-Tech, MBA | 15 |
| Expert -3 | Automobile | MBA | 7 |
| Expert -4 | Supply Chain Management | Post Doc | 11 |
| Expert -5 | Mining and Metal | M-Tech, MSc | 16 |
| Expert -6 | Manufacturing | MBA | 12 |
| Expert -7 | Supply Chain Management | M.Tech | 14 |

The experts were provided a questionnaire survey in which they filled in their inputs regarding the acceptance of the identified CSFs for supply chain resilience. An open conversation allowed the authors to note down the thoughts and recommendations of the experts, and finally, only the CSFs that all the experts accepted were finalized. The final selected criteria and CSFs are showcased in Tables 2 and 3, respectively, along with their descriptions, impacts on industries, and references.

**Table 2:** Identified criteria along with their description and impact on the industry

| S. No. | Criteria | Description | Impact on industry | References |
|---|---|---|---|---|
| **C1** | Cost-effectiveness | Cost-effectiveness is the ratio of the value or benefit gained to the cost incurred. Being more cost-effective would mean the organizations are getting the greatest profit for the least cost. | An organization that is not cost-effective might make bad investments and lead to bigger problems in the long run. | Hosseini et al., 2019<br>Agarwal et al., 2020 |
| **C2** | Technological Advancement | A higher level of technological advancement will allow the companies to introduce new and improved methods for opposing interruptions and reducing delays, thus improving their performance, efficiency, and resilience. | Advancement of technological capabilities induces better performance and allows for innovative ways to combat disruptions. | Jain et al., 2017<br>Rajesh, 2017 |
| **C3** | Government Policies and Regulations | Government policies and regulations help support organizations in adopting I5.0 practices for achieving sustainable and resilient supply chain practices. | If appropriately used, policies, regulations, and incentives can enable any industry to adopt the necessary practices to become sustainable and resilient. | Blessley and Mudambi, 2022 |
| **C4** | Wastage Minimization | Wastage minimization will help the organizations achieve better control over the resources, helping them move towards sustainable supply chain practices and thus meet the goal of becoming resilient. | Any organization that looks to minimize wastage and become sustainable must know its processes and products inside out. This knowledge will undoubtedly aid industries in becoming resilient. | Hosseini et al., 2019 |

**Table 3:** Identified CSF along with their description and impact on the industry

| Sr. No. | Critical Success Factors | Description and their impact on the industry | References |
|---|---|---|---|
| **$CSF_1$** | Disruption awareness | A supply chain can recognize imminent obstructions that might cause delays or interruptions and simultaneously anticipate and react to the market demand proactively. Control can be maintained over such circumstances with the help of technologies like IoT, big data, 5G and beyond, and shop floor trackers to anticipate and pre-emptively coordinate, share information, and collaborate with parallel supply chains. | Chowdhury and Quaddus, 2017<br>Jani et al., 2017<br>Singh et al., 2019<br>Blessley and Mudambi, 2022<br>Quieroz et al., 2022 |
| **$CSF_2$** | Operational robustness | It is the quality of a supply chain to maintain its operations in the face of any challenge. It can be characterized as the readiness level to oppose and sustain any disruptions by constantly evolving to reduce the impact on performance. Robustness can be achieved by rigorous testing of distribution networks using digital twins, advanced simulation, and application of smart sensors in cyber-physical systems. Training can also be provided to operations managers using augmented and virtual reality. | Chowdhury and Quaddus, 2017<br>Karl et al., 2018<br>Singh et al., 2019<br>Agarwal et al., 2020<br>Blessley and Mudambi, 2022 |

| | | | |
|---|---|---|---|
| **$CSF_3$** | Visibility | A supply chain can gather accurate information about the status of the transiting elements, providing a clear view of the upstream and downstream inventories and allowing the organizations to be ready for any disruptions in demand and supply. Problems can be solved in the discovery phase by using IoT, smart sensors, and shop floor trackers to provide a higher level of real-time monitoring, allowing for strategic decisions to be made with the help of AI and complex adaptive systems. | Kamalahmadi and Parast 2016<br>Jani et al., 2017<br>Karl et al., 2018<br>Hosseini et al., 2019<br>Singh et al., 2019<br>Remko, 2020<br>Sabahi & Parast, 2020<br>Agarwal et al., 2020<br>Nikookar and Yanadori, 2021<br>Blessley and Mudambi, 2022<br>Quieroz et al., 2022 |
| **$CSF_4$** | Knowledge management | It can be described as the socializing power of supply chain managers that will allow them to maintain healthy social relationships with other supply chain members, allowing for selective information sharing and better collaboration. It also includes the managerial human capital, i.e., the hands-on knowledge attained by a manager during their tenure, which can be stored and managed using cloud storage, big data, and AI-based management systems. The new managers can then be trained using this knowledge bank through extended reality, digital twin, virtual training, etc. | Kamalahmadi and Parast 2016<br>Karl et al., 2018<br>Sabahi & Parast, 2020<br>Agarwal et al., 2020<br>Nikookar and Yanadori, 2021<br>Blessley and Mudambi, 2022<br>Quieroz et al., 2022 |

| | | | |
|---|---|---|---|
| **$CSF_5$** | Building redundancy | Having buffer stock and backup energy resources in events of supply disruptions will allow firms to cope and adapt to any situation by providing managers additional time to come up with effective solutions. Using renewable energy sources, smart manufacturing, shop floor trackers, and AI-enabled cyber-physical systems will help build minimal backup stock for smoother functioning. | Kamalahmadi and Parast 2016<br>Chowdhury and Quaddus, 2017<br>Jani et al., 2017<br>Rajesh, 2017<br>Karl et al., 2018<br>Hosseini et al., 2019<br>Singh et al., 2019<br>Remko, 2020<br>Sabahi & Parast, 2020<br>Agarwal et al., 2020<br>Blessley and Mudambi, 2022<br>Queiroz et al., 2022 |
| **$CSF_6$** | Flexibility | Flexibility in a supply chain can be described as a firm's ability to adapt and meet the varying market demands with minimum resource utilization. It includes flexible production facilities, flexibility in sourcing and distribution, flexible storage capacity, and workforce arrangements. Introducing hyper customization, additive manufacturing, collaborative robotics, and AI-based management systems will help improve product variety, manage workforce needs, and make better sourcing and distribution links decisions. | Kamalahmadi and Parast 2016<br>Chowdhury and Quaddus, 2017<br>Jani et al., 2017<br>Rajesh, 2017<br>Karl et al., 2018<br>Hosseini et al., 2019<br>Singh et al., 2019<br>Sabahi & Parast, 2020<br>Agarwal et al., 2020<br>Nikookar and Yanadori, 2021<br>Blessley and Mudambi, 2022 |

| | | | |
|---|---|---|---|
| **$CSF_7$** | Agility | It can be defined as the ability of a firm to rapidly respond to any changes and react dynamically to fulfill the customer's needs and prevent any major loss. To achieve Agility, a supply chain needs to respond quickly and effectively to unexpected market changes. Technologies like big data, shop floor trackers, digital ecosystems, and AI-based management systems can help increase the supply chain's velocity and Agility. | Kamalahmadi and Parast 2016<br>Chowdhury and Quaddus, 2017<br>Jani et al., 2017<br>Rajesh, 2017<br>Karl et al., 2018<br>Hosseini et al., 2019<br>Singh et al., 2019<br>Remko, 2020<br>Sabahi & Parast, 2020<br>Agarwal et al., 2020<br>Nikookar and Yanadori, 2021<br>Blessley and Mudambi, 2022<br>Quieroz et al., 2022 |
| **$CSF_8$** | Contingency Planning | It is the 'if all else fails' approach adopted by organizations to limit the setback caused by disruption of operations, allowing for quick recovery and absorption of losses up to certain predetermined limits. Using 5G networks and smart sensors for edge computing and semantic interoperability will ensure better resource reconfiguration and a faster restoration time to the pre-disruption phase. | Chowdhury and Quaddus, 2017<br>Jani et al., 2017<br>Hosseini et al., 2019<br>Agarwal et al., 2020<br>Nikookar and Yanadori, 2021<br>Blessley and Mudambi, 2022 |

| | | | |
|---|---|---|---|
| **$CSF_9$** | Innovation | It allows the companies to overcome any disruptions or disturbances in an unrecognized, imaginative, and dynamic way, brought about by an organization-wide set of goals for promoting growth and ensuring long-term survival. A firm's innovative ability is limited by its technological capability. Adopting technologies like IoT, big data, AI, smart manufacturing, collaborative robotics, digital twin, etc., will allow firms to develop more innovative ways of dealing with disruptions. | Kamalahmadi and Parast 2016<br>Remko, 2020<br>Sabahi & Parast, 2020 |
| **$CSF_{10}$** | Sustainability | It can be described as the characteristic of a company to resolve its problems without compromising the ability of future generations to meet their needs. A sustainable supply chain supports resiliency by reducing the risks associated with the depletion of earth's resources. Waste prevention, green computing, additive manufacturing, smart manufacturing, and use of renewable energy sources are some ways to achieve a sustainable supply chain. | Jani et al., 2017<br>Singh et al., 2019 |

The factors that are vital to the success of any business or organization are known as critical success factors (Boynton and Zmud, 1984). To simply put, a CSF is a key element that holds a significant influence over the overall success and performance of any entity. There are many factors listed in the literature that can help a supply chain achieve resilience, however, not all can be deemed important as a high number of factors lead to complexity in implementation and decision making (Kannan, 2018). Hence, organizations need to utilize the CSF theory which draws parallels from the Pareto principle (Bhatia & Kumar, 2020), that is, majority of the issues to the achievement of resilience in a supply chain can be resolved by tackling only a few factors which are critical to the operations. The above-listed factors are called CSFs as they have been shortlisted through rigorous research using the PRISMA 2020 statement with further refinement through expert opinions and the use of Delphi method.

The next section explains the methodology adopted by the authors for further filtering these CSFs using their driving and dependence powers and ranking them using the criteria weights to provide industries with a framework for adopting resilient supply chains.

## 3. Methodology

This section showcases the four-phased methodology adopted by the authors for the study. In the first phase, PF-AHP is used to evaluate the criteria weights. Pythagorean fuzzy sets are integrated with AHP, which is preferred over the other available and widely used methodologies such as ANP, SWARA, ENTROPY, etc., due to its ability to handle qualitative as well as quantitative data. It helps resolve any issues the decision-makers face by using its hierarchical framework and allows them to assess the evaluation procedure's consistency (Lahane and Kant, 2021). In the second phase, the m-TISM approach and MICMAC analysis are applied to evaluate the interrelationships of the CSFs and further classify them based on their dependence and driving power. The m-TISM approach is adopted as an enhanced version of the ISM methodology, which enables the depiction of the interrelationships of the CSFs in a hierarchical design (Meena and Dhir, 2021), helping to establish a better understanding of the CSFs that are critical to supply chain resilience. In the third phase, PF-CoCoSo is applied by using the criteria weights calculated in PF-AHP to rank the CSFs in priority order. CoCoSo is employed due to the higher reliability and stability offered compared to other techniques. Moreover, the Pythagorean fuzzy sets are integrated similarly to PF-AHP to account for any uncertainties (Lahane and Kant, 2021). Finally, sensitivity analysis is done to check the robustness of the framework. The methodology followed will allow for assigning weights to the criteria and prioritization of the CSFs as well as highlighting the pathway to achieve them.

### *3.1 PF-AHP*

The analytic hierarchy process (AHP) is a powerful and widely used tool that many researchers and policymakers have employed to solve MCDM problems (Vaidya and Kumar, 2006). Introduced by Saaty, AHP helps in making decisions when multiple criteria are involved (Chou et al., 2014), and it helps in setting priority by assessing the relative importance of each criterion concerning one another (Darko et al., 2019). The current research will make use of Pythagorean Fuzzy AHP (PF-AHP), which combines Pythagorean fuzzy numbers with AHP to decrease ambiguities and handle the imprecise nature of the work, thus improving the reliability of the results produced (Ilbahar et al., 2018). The Pythagorean fuzzy sets, which were introduced in 2013 by Yager, are actually an extension of the intuitionistic fuzzy sets and are used to provide a higher level of flexibility for reasoning, which sits well with the human standards by increasing the area under consideration (Sindhwani et al., 2022a). The steps to be followed are described in detail by Ilbahar et al. (2018) and Lahane and Kant (2021). Firstly, the expert opinion recorded in linguistic terms is used to create a pairwise comparison matrix and then converted into interval-valued Pythagorean fuzzy numbers, showcased in Table 4, using the conversion scale provided by Ilbahar et al. (2018). Then computations for differences matrix followed by interval multiplicative matrix and calculation for determinacy value are performed. Finally, the weight matrix is created, after which normalization is done to obtain the criteria weights. The final criteria weights obtained are shown in Table 5.

After finalizing the criteria weights, the authors worked on the analysis of the CSFs, starting with m-TISM. Even though there are many research methods available to rank and prioritize the CSFs, such as the MOORA tool, CoCoSo, Best Worst Methods, etc., none of them are capable of constructing the interrelationships and hierarchical order between the CSFs (Sindhwani et al., 2022 b). M-TISM can be used to convert a poorly defined mental model of systems into a well-defined and justified one (Meena and Dhir, 2020). Hence, the authors have employed m-TISM to develop a hierarchical model to interpret the relationships between the CSFs and then used the MICMAC analysis to categorize the CSFs into four clusters according to their dependence and driving power.

Table 4: Pairwise comparison matrix with IVPFNs

| Criteria | C1 | | | | C2 | | | | C3 | | | | C4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | m(L) | m(U) | n(L) | n(U) | m(L) | m(U) | n(L) | n(U) | m(L) | m(U) | n(L) | n(U) | m(L) | m(U) | n(L) | n(U) |
| C1 | 0.1965 | 0.1965 | 0.1965 | 0.1965 | 0.45 | 0.55 | 0.45 | 0.55 | 0.55 | 0.65 | 0.35 | 0.45 | 0.65 | 0.8 | 0.2 | 0.35 |
| C2 | 0.45 | 0.55 | 0.45 | 0.55 | 0.1965 | 0.1965 | 0.1965 | 0.1965 | 0.45 | 0.55 | 0.45 | 0.55 | 0.65 | 0.8 | 0.2 | 0.35 |
| C3 | 0.35 | 0.45 | 0.55 | 0.65 | 0.45 | 0.55 | 0.45 | 0.55 | 0.1965 | 0.1965 | 0.1965 | 0.1965 | 0.45 | 0.55 | 0.45 | 0.55 |
| C4 | 0.2 | 0.35 | 0.65 | 0.8 | 0.2 | 0.35 | 0.65 | 0.8 | 0.45 | 0.55 | 0.45 | 0.55 | 0.1965 | 0.1965 | 0.1965 | 0.1965 |

Table 5: Final criteria weights

| Criteria | Weights |
|---|---|
| C1 | 0.3830 |
| C2 | 0.3388 |
| C3 | 0.1636 |
| C4 | 0.1145 |

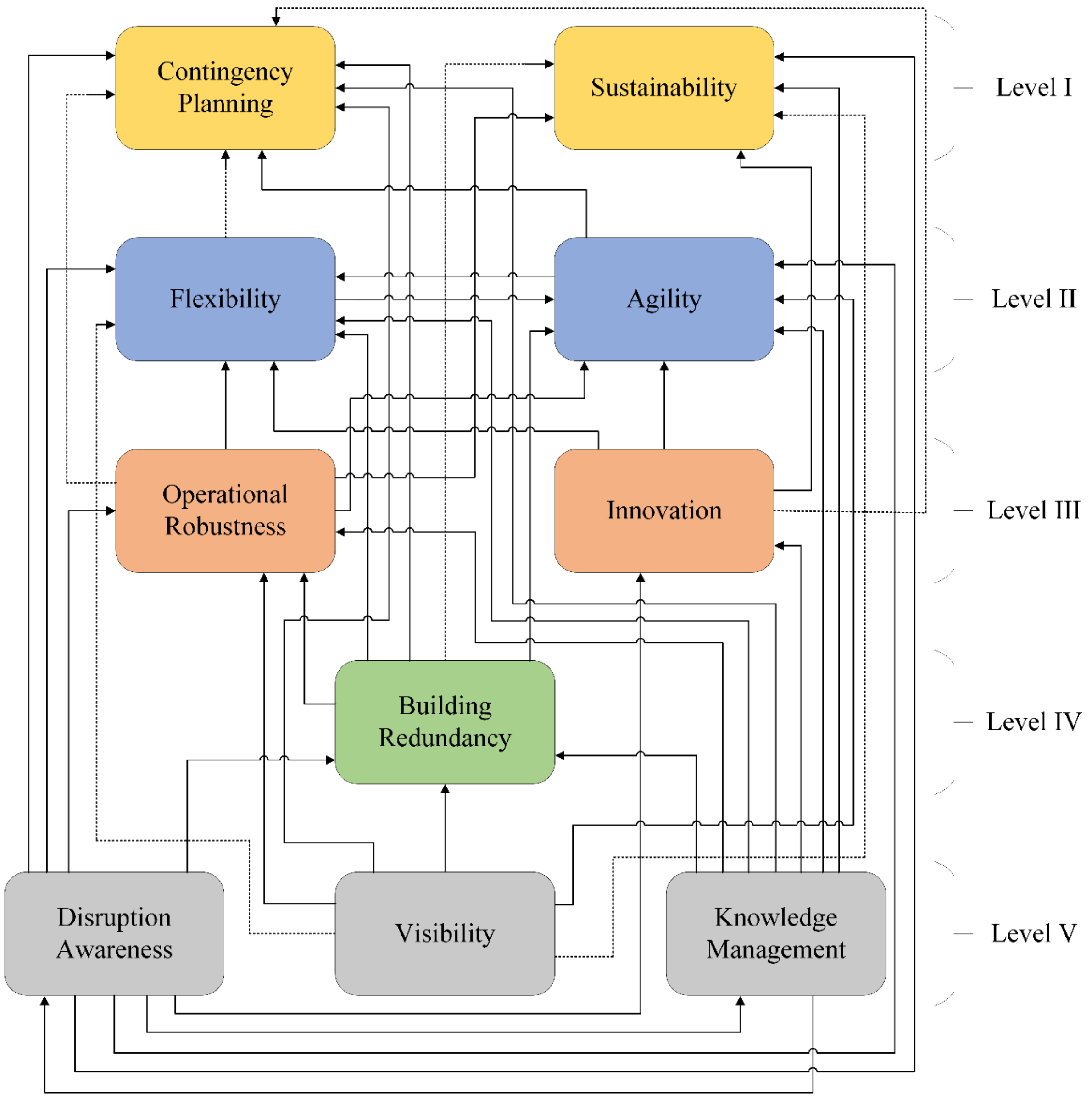
*3.2 m-TISM and MICMAC analysis*

Interpretive structural modelling (ISM) is a technique introduced by Warfield, used for understanding the relationship shared between some specific items which are part of a defined problem (Attri et al., 2013). It is most widely used for identifying the influence of one item over others and has been deemed suitable and applied by many researchers for visualizing the direct as well as indirect relationships between the variables (Raut et al., 2017). However, ISM had several drawbacks, and thus it was upgraded to TISM (Total Interpretive Structural Modelling), developed to resolve the key limitations of ISM (Jena et al., 2017). TISM looks to improve on its predecessor by defining the contextual relationship between the elements and by interpreting the nodes as well as the links to provide better application in real-life situations (Sushil, 2012). Quickly adopted by researchers, TISM still had a major issue associated with it regarding the number of comparisons that needed to be made by the experts. For instance, in a scenario containing '$x$' variables, the total number of paired comparisons needed to be made is $x(x-1)/2$, which makes the process quite tiring when ten or more variables are involved (Sushil, 2017). Hence, the use of m-TISM (modified Total Interpretive Structural Modelling) was proposed by Sushil (2017) to reduce the number of paired comparisons by performing simultaneous transitivity checks and eliminating additional steps of ISM/TISM (Meena and Dhir, 2020). The m-TISM methodology successfully answers the 3W-H questions, that is, "what, why, when, and how," while reducing the pairwise comparisons (Sindhwani et al., 2022b) and is thus preferred over both ISM and TISM for evaluating the interrelationships of the ten selected CSFs.

The steps to be followed for m-TISM, as discussed by Sushil, 2017, begin with constructing a pair comparison matrix created using the expert's input about the contextual relationship of the CSFs and the reasons for the interpretation. This initial matrix is then converted into a binary reachability matrix along with simultaneous transitivity checks to obtain the fully transitive reachability matrix. The transitive rule states that if one of the CSFs (say 'A') has a relation with another CSF (say 'B') and 'B' has a relationship with another CSF (say 'C'), that is, A→B and B→C then, A shares a transitive relationship with C (A→C). The transitive links are usually denoted separately as 1*. Next, the hierarchical partitioning (Table 6) is done by comparing the reachability sets (rows) with the intersection set of reachability and antecedent (columns) sets. The CSFs for which the reachability and intersection sets are the same are denoted as level 1, and the steps are continued until all the CSFs get assigned a hierarchical level. In the next step, the digraph is created using hierarchical partitioning and the fully transitive reachability matrix consisting of direct and transitive links. Finally, the digraph is translated into the m-TISM model showcased in Figure 2.

Table 6: Hierarchical partitioning of CSFs

| S. No. | Critical Success Factor (CSF) | Level |
|---|---|---|
| **CSF8** | Contingency Planning | I |
| **CSF10** | Sustainability | I |
| **CSF6** | Flexibility | II |
| **CSF7** | Agility | II |
| **CSF2** | Operational Robustness | III |
| **CSF9** | Innovation | III |
| **CSF5** | Building redundancy | IV |
| **CSF1** | Disruption awareness | V |
| **CSF3** | Visibility | V |
| **CSF4** | Knowledge management | V |




A straight line represents Direct Link and a dotted line represents Transitive Link

Figure 2: m-TISM model

The authors also performed MICMAC analysis to divide the CSFs into four clusters based on their dependence and driving power found by using the fully transitive reachability matrix. All the relations (direct or transitive) are summed across the whole row to find the driving power of the particular CSF, and the same is done along the column to find the dependence of that CSF, as shown in Table 7. Here, '1' represents a direct link, and '*1*' illustrates a transitive link. Then, a graph is created and divided into four quadrants, and CSFs are mapped according to the dependence and driving power, as shown in Figure 3.

Table 7: MICMAC analysis

| **CSFs** | **CSF1** | **CSF2** | **CSF3** | **CSF4** | **CSF5** | **CSF6** | **CSF7** | **CSF8** | **CSF9** | **CSF10** | **Driving Power** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **CSF1** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 |
| **CSF2** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | *1* | 0 | 1 | 5 |
| **CSF3** | 0 | 1 | 1 | 0 | 1 | *1* | 1 | 1 | 0 | *1* | 7 |
| **CSF4** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 |
| **CSF5** | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | *1* | 6 |
| **CSF6** | 0 | 0 | 0 | 0 | 0 | 1 | 1 | *1* | 0 | 0 | 3 |
| **CSF7** | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 3 |
| **CSF8** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| **CSF9** | 0 | 0 | 0 | 0 | 0 | 1 | 1 | *1* | 1 | 1 | 5 |
| **CSF10** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| **Dependence** | 2 | 5 | 1 | 2 | 4 | 8 | 8 | 9 | 3 | 7 | |

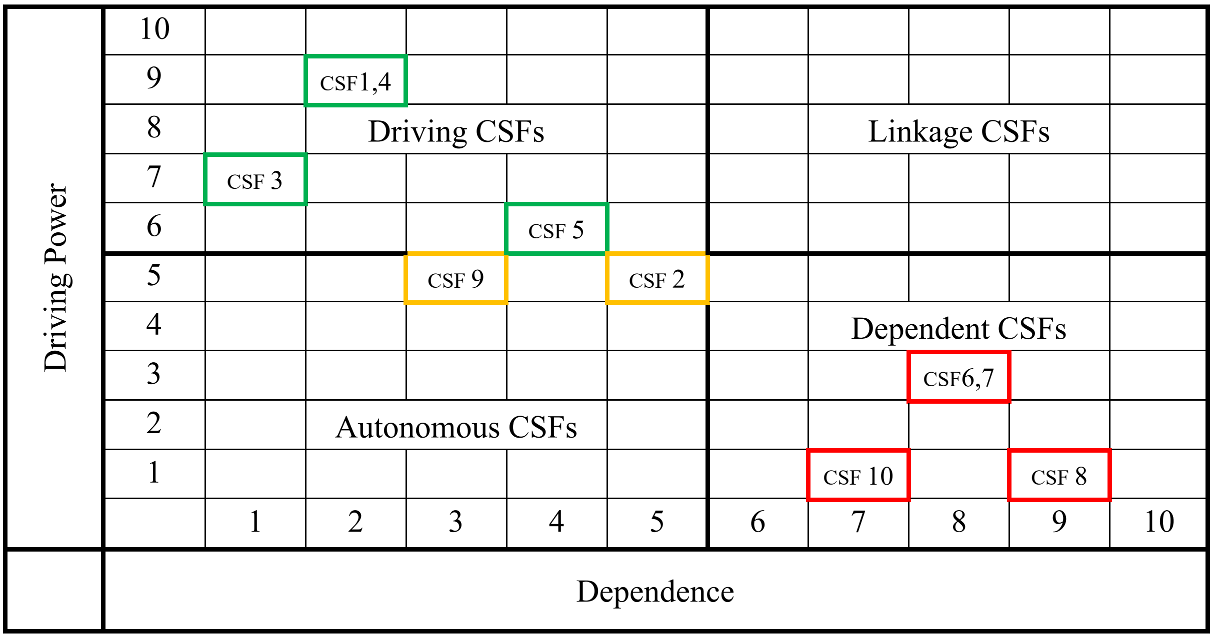



Figure 3: MICMAC analysis cluster chart

The four clusters, as shown in Figure 3, are:

Cluster 1 (Autonomous CSFs) – As evident from the Figure 3, the CSFs in this cluster have lower driving powers and lower dependence, implying that the CSFs in this cluster are neither dependent on other CSFs nor do they drive them. CSF 2 and CSF 9 fall under this category.

Cluster 2 (Dependent CSFs) – The CSFs in this cluster have low driving powers but high dependence, meaning that these CSFs are reliant on other CSFs and are not particularly helpful in promoting others. CSFs 6, 7, 8, and 10 come under this cluster.

Cluster 3 (Linkage CSFs) – These CSFs have high dependence and driving power and are the most difficult to interpret, as any wrong decision regarding them can create a cascading effect.

Cluster 4 (Driving CSFs) – These CSFs have high driving powers and low dependence, which means that these CSFs are highly crucial as many other CSFs are dependent on them, and achieving these will create a major impact. CSFs 1, 3, 4, and 5 belong to this category.

From the above classification, it is easy to see and realize that CSF 8 (Contingency Planning) and CSF 10 (Sustainability) have a driving power of only one each. This means that they only drive themselves and have no effect whatsoever on any other CSFs. Thus, both these CSFs were excluded from further analysis. The final CSFs included in the further analysis for prioritizing and ranking are CSFs 1, 2, 3, 4, 5, 6, 7, and 9.

After evaluating the interrelationships of the CSFs and the construction of the hierarchical model, there is still a need to rank and prioritize the CSFs to provide industries with specific areas to focus on to improve the resilience of their supply chains. Thus, in the next step, PF-CoCoSo ranks the CSFs in priority order using the weightage of the criteria calculated in PF-AHP to provide the industries with a path to achieve supply chain resilience using I5.0 technologies. The authors have used PF-CoCoSo for ranking the CSFs as it makes use of three aggregation strategies for calculating the results as compared to, say, only one in PF-TOPSIS, making the results of PF-CoCoSo highly reliable and the difference between the alternatives (CSFs in this case) more obvious (Liao et al., 2020).

### *3.3 PF-CoCoSo*

Combined Compromise Solution (CoCoSo) was introduced by Yazdani et al., 2018 and is based on an integrated SAW (simple additive weighting) and EWP (exponentially weighted product) model (Khan and Haleem, 2021). For PF-CoCoSo, similar to PF-AHP, Pythagorean fuzzy sets are utilized to deal with the ambiguous and uncertain nature of the problem (Sindhwani et al., 2022a). The steps to be followed are described in detail by Lahane and Kant, 2021. Firstly, expert opinion is recorded in linguistic terms to create a decision matrix, which is then converted into Pythagorean fuzzy numbers using the scale of linguistic terms provided by Liu et al., 2021. From this, a score function matrix is generated and subsequently converted into an orthonormal Pythagorean fuzzy matrix. Then, the weighted comparability sequence and power-weight comparability sequence total are calculated using aggregation strategies to calculate the relative score. Finally, these scores obtained are used to find the final assessment value, providing us with the CSFs' rank. The final ranking of the CSFs is provided in Table 8.

Table 8: Final ranking of CSFs

| CSFs | $k_{ia}$ | $k_{ib}$ | $k_{ic}$ | $k_i$ | Rank |
|---|---|---|---|---|---|
| **CSF1** | 0.162717 | 6.731509 | 0.996195 | 3.659649 | 1 |
| **CSF2** | 0.145901 | 5.742179 | 0.89324 | 3.168332 | 4 |
| **CSF3** | 0.120947 | 4.388927 | 0.740464 | 2.482631 | 7 |
| **CSF4** | 0.044056 | 2 | 0.269721 | 1.058767 | 8 |
| **CSF5** | 0.148877 | 5.979924 | 0.91146 | 3.279479 | 2 |
| **CSF6** | 0.111765 | 4.672399 | 0.684254 | 2.532418 | 6 |
| **CSF7** | 0.136553 | 6.020324 | 0.836008 | 3.213452 | 3 |
| **CSF9** | 0.129184 | 5.381319 | 0.790894 | 2.919694 | 5 |

After finalizing the rank of the CSFs, there arises a need for validating the results of the framework. Sensitivity analysis is a technique that is useful for identifying elements and checking the model framework's response with respect to specific inputs, with the latter being used for verification and validation of the model (Christopher and Patil, 2002). Thus, the authors have implemented a sensitivity analysis in the next section of the study to check the robustness of the results and thereby validate them.

*3.4 Sensitivity Analysis*

The data for any MCDM problem collected has a certain vagueness associated with it. The smallest changes in the relative weights can lead to huge changes in the final rankings (Mangla et al., 2017). It is necessary to check the framework's behavior under different conditions to validate it (Sindhwani et al., 2022a). In this regard, sensitivity analysis is conducted, which helps validate the proposed framework's robustness (Wang et al., 2020).

For conducting the sensitivity analysis, the authors varied the weightage of the criteria on a scale of 0.9 to 0.1 times the criteria weight with a decrement of 0.1 each time, thus conducting nine experiments for each criteria. Criteria C1 and C2 were chosen to conduct the sensitivity analysis as they carry the majority weightage, and any change in their weight will be very likely to impact the overall ranking.

Firstly, criteria C1 (Cost-effectiveness) with a criteria weight of 0.3830 was varied from 0.9 times the criteria weight to 0.1 times. The changes in the weightage of all the criteria were recorded as shown in Table 9. The criteria weights obtained from these variations were used to calculate the ranks of the CSFs once again, and the variations observed in the ranks are provided in Table 10 and also showcased graphically in Figure 4.

Similarly, criteria C2 (Technological Advancement) with a criteria weight of 0.3388 was also varied on the same scale to obtain the variations in criteria weights displayed in Table 11, along with the variations in the rankings as shown in Table 12 and graphically represented in Figure 5.

As evident from the graphs, the variations observed in the rankings are minimal as the graph retains its shape mostly, thus proving that the framework is robust and will withstand any external variations.

Table 9: Criteria weight variations when weightage of C1 was varied

| **Criteria** | **Normal** | **0.9** | **0.8** | **0.7** | **0.6** | **0.5** | **0.4** | **0.3** | **0.2** | **0.1** |
|---|---|---|---|---|---|---|---|---|---|---|
| C1 | 0.383048 | 0.3447 | 0.3064 | 0.2681 | 0.2298 | 0.1915 | 0.1532 | 0.1149 | 0.0766 | 0.0383 |
| C2 | 0.338796 | 0.3598 | 0.3809 | 0.4019 | 0.4229 | 0.4440 | 0.4650 | 0.4860 | 0.5071 | 0.5281 |
| C3 | 0.163632 | 0.1738 | 0.1840 | 0.1941 | 0.2043 | 0.2144 | 0.2246 | 0.2347 | 0.2449 | 0.2551 |
| C4 | 0.114524 | 0.1216 | 0.1287 | 0.1359 | 0.1430 | 0.1501 | 0.1572 | 0.1643 | 0.1714 | 0.1785 |

Table 10: Rank variations observed when weightage of C1 was varied

| **CSFs** | **Normal** | **0.9** | **0.8** | **0.7** | **0.6** | **0.5** | **0.4** | **0.3** | **0.2** | **0.1** |
|---|---|---|---|---|---|---|---|---|---|---|
| CSF1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| CSF2 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 |
| CSF3 | 7 | 7 | 7 | 7 | 7 | 6 | 6 | 6 | 6 | 5 |
| CSF4 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| CSF5 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| CSF6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 4 | 3 | 3 |
| CSF7 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 6 |
| CSF9 | 5 | 5 | 5 | 5 | 6 | 7 | 7 | 7 | 7 | 7 |

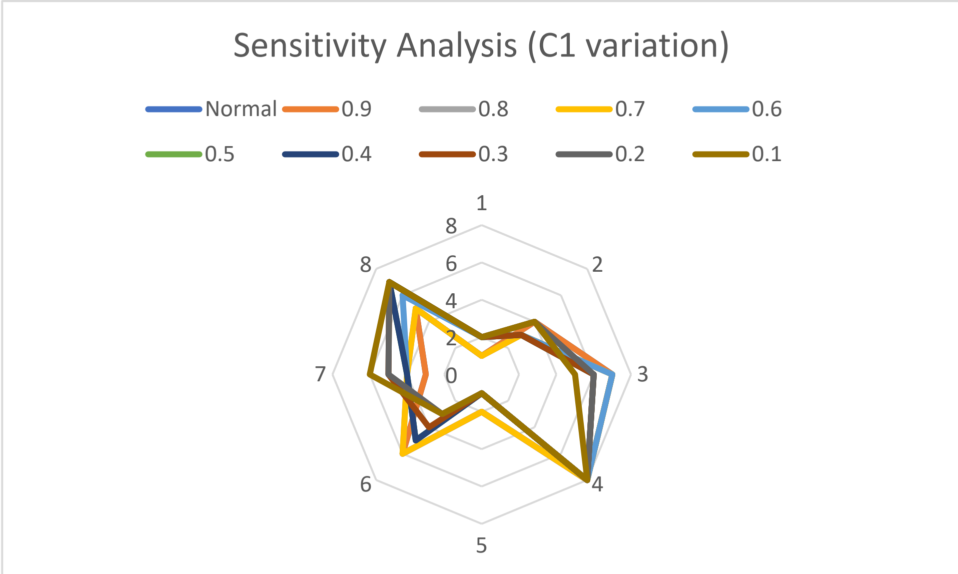


Figure 4: Graphical representation of rank variations in case of C1

Table 11: Criteria weight variations when weightage of C2 was varied

| Criteria | Normal | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 |
|---|---|---|---|---|---|---|---|---|---|---|
| C1 | 0.383048 | 0.4027 | 0.4223 | 0.4419 | 0.4616 | 0.4812 | 0.5008 | 0.5204 | 0.5401 | 0.5597 |
| C2 | 0.338796 | 0.3049 | 0.2710 | 0.2372 | 0.2033 | 0.1694 | 0.1355 | 0.1016 | 0.0678 | 0.0339 |
| C3 | 0.163632 | 0.1720 | 0.1804 | 0.1888 | 0.1972 | 0.2056 | 0.2139 | 0.2223 | 0.2307 | 0.2391 |
| C4 | 0.114524 | 0.1204 | 0.1263 | 0.1321 | 0.1380 | 0.1439 | 0.1497 | 0.1556 | 0.1615 | 0.1673 |

Table 12: Rank variations observed when weightage of C2 was varied

| CSFs | Normal | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 |
|---|---|---|---|---|---|---|---|---|---|---|
| CSF1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
| CSF2 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| CSF3 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| CSF4 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| CSF5 | 2 | 3 | 3 | 4 | 5 | 5 | 5 | 5 | 5 | 5 |
| CSF6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| CSF7 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 |
| CSF9 | 5 | 5 | 5 | 3 | 3 | 3 | 3 | 2 | 2 | 1 |

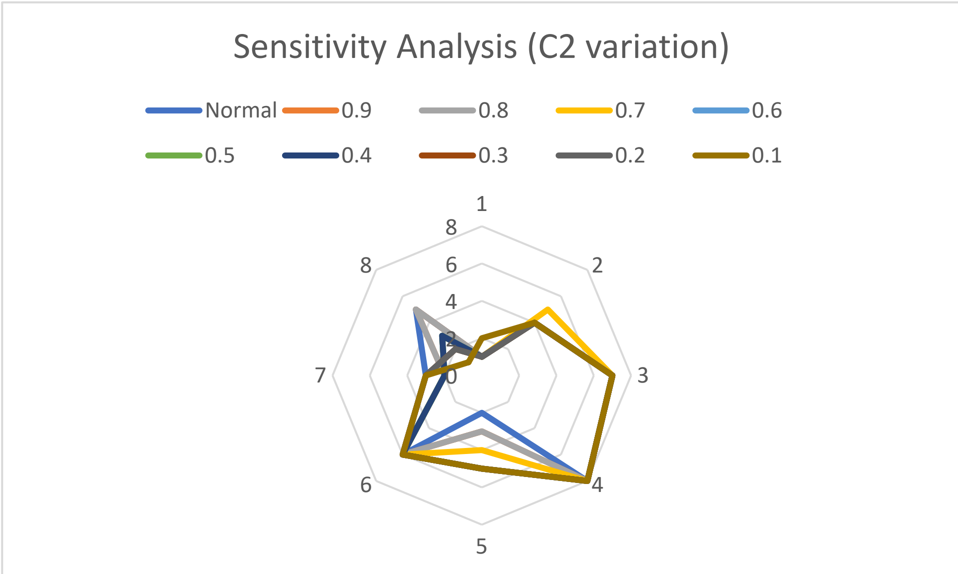



Figure 5: Graphical representation of rank variations in case of C2

## 4. Discussion

The study aimed to identify and rank the criteria and CSFs of supply chain resilience and develop an understanding of how the prioritized CSFs can be attained with the help of I5.0 technologies. Section 2 and Section 3 have adequately dealt with identifying and ranking the criteria and the CSFs. In this section, we will be discussing the study's results by trying to understand the reasoning for the ranking established as well as how and which I5.0 technology can help us achieve supply chain resilience.

We begin with the analysis of the criteria for supply chain resilience. From the results of PF-AHP, it can be seen that criteria C1, Cost-effectiveness, achieved the highest weightage of all the four criteria, scoring a weight of 0.3830. Cost-effectiveness can be defined as the ratio of benefits received to costs incurred. To elaborate, it is the measure of the resilience achieved per unit of investment, which means that higher cost-effectiveness indicates that the firm was successful in becoming resilient at minimum cost, thus ensuring that higher profitability margins are maintained. The cost-effectiveness of a strategy to be adopted plays a very big role as every strategy will have certain costs associated with it, and any firm looking to make its supply chain resilient will need to know the cost-to-benefit ratio of the strategy so that it can take the optimized decision regarding the direction in which they want to proceed. Simulation is a great tool and can help analyze supply chain resilience strategies for short- and long-term disruptions. Tan et al., 2020 suggest using a simulation-based model to analyze the supply chain network structure by capturing the dynamics of disruption and recovery to determine the optimum strategy for building a resilient supply chain. Ivanov, 2018 has conducted a simulation-based study to understand the ripple effect during supply chain disruptions and the factors that might enhance or help mitigate the ripple effect. Many similar studies have been conducted to explore the use of proactive mitigative strategies and reactive contingency strategies using simulation analysis. Digital Twins, mixed reality, and advanced simulation are all I5.0 technologies that can help in recognizing the cost-effectiveness of any particular strategy; moreover, various mathematical models can be developed and vigorously tested using AI and simulation to help estimate the investments that a firm might need to make in order to adopt supply chain resilience. Any firm will only invest in new technologies and strategies if they are time-tested and verified, and I5.0 technologies can help validate these strategies to improve the resilience of the supply chains.

The second highest weightage was achieved by criteria C2, Technological advancement, with a criteria weight of 0.3388. Technological advancement refers to measuring the latest technologies employed by the organization and its supply chain members to overcome or even predict and evade potential disruptions. A supply chain is only as strong as its weakest link (Clendenin, 1997), and a firm's success is tied in with its weakest supply chain member (Spekman et al., 1998). This means that if one of the members of a supply chain is lacking in the technological area, then the rest of the members are also reduced to the same level of technology, irrespective of their actual advancement in the use of the latest technologies. A simple example of this can be a three-member supply chain consisting of A, B, and C as the members, where A and C are using the latest technologies, ensuring better and faster communication. However, member B is still relying on older technologies and is thus having a relatively slower communication speed. If any information was to be communicated to the other two members by A, then the time taken for communicating the message will be when B receives and processes the information. This can especially be very devastating for the visibility and awareness of a supply chain. Hence, it can be said that the technological advancement of the supply chain members directly reflects the strength and resilience of the supply chain. A firm that can sense the supply disruption can invoke business continuity plans to alter production schedules or source from secondary suppliers in order to meet customer demands (Balakrishnan and Ramanathan, 2021). Utilization of advanced technologies, such as IoT, 5G-6G, shop floor trackers, and cyber-physical systems (CPS), which all come under the umbrella of I5.0, can help in improving the resilience of a supply chain by meeting the needs of the CSFs of supply chain resilience. The prominence of cost-effectiveness and technological advancement as the top criteria underscores the fundamental role of efficient resource utilization and the adoption of cutting-edge technologies in achieving supply chain resilience. Organizations should recognize that investments in I5.0 technologies, such as IoT, big data analytics, AI, and digital twins, are advantageous and increasingly necessary to enhance disruption awareness and response capabilities.

Criteria C3 (Government Policies and Regulations) and C4 (Wastage Minimization) received the third and fourth highest criteria weights at 0.1636 and 0.1145, respectively. Even though they received lower criteria weights, both criteria remain significant for a supply chain to achieve resilience. Government policies can form a crucial part of the resilience capability of any industry's supply chain as they can be the deciding factor for the measures to take by a firm facing disruptions. For example, in the food supply chain industry, key governmental institutions such as The World Bank, agricultural ministries, and even private sector institutions can improve the resilience of the sector by choosing the crops, cultivators, species, and breeds that are less likely to be affected by disasters such as floods, droughts, etc. and also offer good nutritional value (Davis et al., 2021). Certain incentives can also be provided to industries for adopting new technologies, which, as discussed under technological advancement, will also help in making the supply chains more resilient. Lastly, wastage minimization can also help achieve supply chain resilience as it directly ties in with the cost-effectiveness of a firm, which is the highest weighted criteria among all. Any firm that looks to reduce its excess waste of any form, be it material, process, time, or distance, will directly influence the profit margins and help generate the funds for technological advancement from within the firm itself. Wastage minimization can also be associated with lean philosophy, which aims to minimize all waste types within a process/industry. Benitez et al., 2018 have highlighted that lean and resilience practices are closely related to each other, with lean acting as a driver of supply chain resilience, thus improving the supply chain performance. I5.0 technologies such as additive manufacturing (AM), simulation, shop floor trackers, and CPS can help minimize wastage and hence make supply chains more resilient. From the results of PF-AHP, we can ascertain the weightage of all criteria used to rank the CSFs in PF-CoCoSo.

After the analysis of the criteria, we moved to the evaluation of the CSFs, starting with m-TISM. The results of m-TISM enabled us to develop a hierarchy-based model and establish the interrelationships between the CSFs. The CSFs Disruption Awareness, Visibility, and Knowledge Management achieved the highest level in the model at level 5, which signifies their importance in the hierarchical model as the CSFs that drive other CSFs, meaning that if attained by an organization, they can help improve the attainability of the other remaining CSFs. They are followed by Building Redundancy at level 4, Operational Robustness and Innovation at level 3, Flexibility and Agility at level 2, and finally, Contingency Planning and Sustainability at level 1, which means that contingency planning and sustainability do not help in the attainment of any other mentioned CSFs and thus are at the bottom level in the model. The direct and transitive relationships of the CSFs are also shown in the model, represented by straight and dotted lines, respectively. The m-TISM model allows us to understand which CSFs are more important and their relation with other CSFs at lower levels. MICMAC analysis results help us differentiate the CSFs into four clusters according to their dependence and driving power. Four of the ten CSFs had high driving and low dependence powers, allowing them to enter the driving cluster. Two CSFs had low dependence and driving powers, and thus they were put into autonomous clusters. The remaining four had high dependence and low driving powers, thus placing them in the dependent cluster. Among the four CSFs in the hanging cluster, CSF 8 (Contingency Planning) and CSF 10 (Sustainability) had the lowest driving power of only one. This meant that both these CSFs were only responsible for driving themselves and did not have any driving effect on any other CSF whatsoever. Hence, both the CSFs were excluded from further analysis as it is established that they should be at a lower priority and should only be considered once other CSFs are met and satisfied for achieving supply chain resilience. The results of m-TISM and MICMAC analysis present us with the key CSFs for achieving supply chain resilience, which are then ranked by employing PF-CoCoSo.

After the evaluation of the interrelationships of the CSFs, there is still the need to rank them; hence, we moved to PF-CoCoSo for ranking the CSFs in priority order. PF-CoCoSo uses the results of the previous two methodologies in PF-AHP and m-TISM to rank the key CSFs on the basis of the ascertained criteria weights. From the results of PF-CoCoSo, it can be seen that CSF 1 (Disruption Awareness) received the first rank and is thus the highest priority CSF for achieving supply chain resilience. The results also resonate with the literature where Queiroz et al., 2022 confirmed in their study that supply chain disruption orientation positively affects supply chain alertness, which positively affects resource reconfiguration, supply chain efficiency, and supply chain resilience. The inability of a firm to foresee supply chain disruptions or underestimating its effects can lead to major consequences for the firm (Ribeiro and Povoa, 2018). A highly aware and sensitive supply chain will be able to sense the imminent danger and proactively work to reduce/mitigate its effects and maintain continuous operations. Having the foresight to recognize potential disruptions will not only help develop proper strategies to combat them but can also help evade them altogether. In order to become more resilient, the supply chains need to develop a heightened disruption awareness by combining both digital and human capabilities for collecting, analyzing, and extracting insights from the gathered data to detect and combat the potential disruptions that can affect their operations (Belhadi et al., 2021). I5.0 technologies such as IoT, big data analytics (BDA), CPS, shop floor trackers, digital twins, AI, etc., can all help improve the disruption awareness of a supply chain, thus making it more resilient.

The second rank was achieved by CSF 5, which is Building Redundancy. A firm that is reliant on only one or a few select suppliers is highly susceptible to supply chain disruptions (Nakatani et al., 2018). Having backup stock energy sources or maintaining good relations with secondary suppliers can prove to be a vital step in improving a supply chain's resilience. Building redundancy not only refers to creating a buffer gap between the output and the demand but also means visualizing the complete supply chain to understand the material flow and identify the risks associated with various suppliers. For instance, a firm that is sourcing from multiple suppliers might feel that it is less susceptible to disruptions; however, it might be the case that a majority of its suppliers are dependent on raw materials from the same supply company, meaning that any disruption at the main supplier's end will be carried down the stream and affect the whole supply chain. It is very necessary for a firm to discern the flow of materials and recognize the immediate and indirect links with the members of a supply chain to calculate the need for buffer capacity and backup sources in a highly disruptive scenario (Tan et al., 2019). Seeing the upstream flow of materials can help organizations prepare for supply chain disruptions by seeking and selecting suppliers that improve their disruption preparedness. I5.0 technologies like BDA, IoT, CPS, AI, digital twins, etc., can help understand the material flow and map out suppliers along with the associated risks. In contrast, other technologies like AM, collaborative robotics, and smart materials, etc., can help improve buffer stock and minimize wastage to achieve supply chain resilience.

CSF 7, Agility, was ranked third for achieving supply chain resilience. Supply chain agility can be explained as the speedy optimization of operations during disruptions by detecting and subsequently positioning the supply chain to respond promptly (Mandal, 2012). An agile firm will have considerably reduced lead time and shortened supply chain cycle time, increasing the firm's profitability by ensuring better on time delivery and reduction of non-value adding processes, giving them an edge over their competitors (Li et al., 2017). Agility positively impacts the responsiveness of a firm. It can even be synonymous with resilience as it helps industries combat disruptions and mold market changes to their advantage (Kazancoglu et al., 2022). Becoming agile will allow companies to react quickly and effectively to unexpected disruptions, allowing them to become resilient by acquiring combative strategies that will help them prevail in any condition. I5.0 technologies such as simulation, AI, CPS, IoT, shop floor trackers, and BDA can all help industries become agile and achieve supply chain resilience.

The results are also in agreement with previous literature. Queiroz et al., 2022 confirmed in their study that disruption orientation acts as an antecedent to alertness level, which positively affects resilience in supply chains. Hosseini et al., 2019 concluded in their work that a firm's absorptive capacity is the first line of defense, showing the importance of building redundancy by keeping inventory and having backup suppliers, etc. Agility is the most important aspect of the reactive dimension of supply chain resilience as it helps rapidly reconfigure systems to deal with disruptions (Sabahi and Parast, 2020). Singh et al., 2019 talk about how awareness acts as an indicator for forecasting demand, redundancy in increasing recovery during shutdown, and Agility for reducing lead time and cost. These top three ranked CSFs combine together to make a three-pronged attack on the capability of a supply chain to increase its ability to anticipate, resist, and respond to disruptions, thus improving the resilience of the supply chains. The prioritization of disruption awareness as the highest-ranked CSF emphasizes the critical need for organizations to develop heightened sensitivity to potential disruptions. I5.0 technologies can play a pivotal role by providing real-time data, predictive analytics, and scenario simulations, enabling organizations to detect and mitigate disruptions effectively. Furthermore, the emphasis on building redundancy and Agility as the next two key CSFs underscores the importance of diversifying supplier networks and enhancing supply chain flexibility. Here, I5.0 technologies can aid in mapping material flows, identifying risks, and ensuring the availability of backup sources, ultimately contributing to resilience by minimizing disruption impacts.

These findings underscore the symbiotic relationship between I5.0 technologies and supply chain resilience. Embracing I5.0 is an option and a strategic imperative for organizations looking to bolster their resilience in today's volatile environment. The study's insights are transferable across industries, emphasizing that I5.0 adoption should be a universal consideration for enhancing supply chain practices. This research opens the door to future investigations into how I5.0 technologies can be effectively integrated into supply chain management to achieve the desired resilience, providing a promising avenue for further exploration in this field.

The study results showcase the most important criteria and CSFs that need to be focused on by industries for achieving supply chain resilience. On comparing and contrasting the current technological capabilities of the industries, it is also clear that I5.0 should be the point of focus for organizations that want to make their supply chains resilient. The criteria and CSFs are applicable to all supply chains, irrespective of the industry. Thus, taking necessary steps to meet the same will ensure every industry's supply chain practices are resilient in today's turbulent environment.

### *4.1 Theoretical Implications*

The study has identified, analyzed, and prioritized the criteria and CSFs necessary for adopting supply chain resilience. The results of the novel four-stage hybrid methodology adopted help authors in providing suggestions and recommendations to the industries from a practical and managerial viewpoint. The research revealed cost-effectiveness and technological advancement as the highest weighted criteria, making both of them a priority constraint that needs to be satisfied and guaranteed to become resilient. The results also showcase that disruption awareness, visibility, and knowledge management are the three CSFs at the highest hierarchy level that possess the highest driving power out of all the ten CSFs identified, while sustainability and contingency planning are at the lowest level, having the least possible driving power. On ranking the CSFs in priority order, it was established that disruption awareness, building redundancy, and Agility are ranked as the top three CSFs for achieving supply chain resilience. The results agree with the resource-based view (RBV) theory as well as the dynamic capability view (DCV) theory. The former states that an organization can maintain its advantage over the competitors through its internal resources that are rare, valuable, and inimitable (Galbreath, 2005), while the latter also incorporates the evolving and developing aspect of the organization to reconfigure itself and enhance its effectiveness (Wu, 2010). Even though collaboration between not only the members but also other supply chains is being promoted, a firm can still maintain its competitive advantage because of its highly advanced technologies and the knowledge management and training it can provide to its employees. Thus, I5.0 technologies can help attain supply chain resilience and ensure the firm's profit advantage. The study's results also reflect positively on resource dependence theory (RDT), concerned with external resources' effects on organizational behavior (Hillman et al., 2009). An organization must have established contingency strategies to control the price of goods entering the supply chain. Building redundant capacity can also help with this, as in case of any small-scale disruptions, the organization can use its stock to maintain low costs. The study has thus successfully provided future research propositions for testing the relations of the top-ranked CSFs concerning the said theories.

### *4.2 Managerial Implications*

The above results have allowed the authors to link the criteria and CSFs to achieve supply chain resilience by employing I5.0 technologies. Following are a few key recommendations suggested by the authors.

Recommendation 1. Industries need to enhance their alertness level by using IoT, BDA, and AI to follow and predict disruptions to provide ample time to strategize maintaining operations.

Industries with a higher alertness level will be much more likely to foresee disruptions. They thus will buy additional time for their managers to shift gears and keep the operations running, making them highly prepared in the face of a likely disturbance and resilient. I5.0 technologies such as BDA can help develop supply chain resilience as it is an active enabler of supply chain alertness (Mandal, 2018), which strongly influences a supply chain's efficiency and resilience (Queiroz et al., 2022). BDA can help forecast market demands and sales and detect changes in the supply chain, thus providing firms with better control over their operations by increasing process monitoring and improving the coordination and collaboration between the chain members (Iftikhar et al., 2022). When clubbed with other I5.0 technologies, such as AI and advanced simulation, the data can be used for running various scenarios where different variations can be introduced to find the best possible solution or alternative to combat the detected oncoming disruption. Improved supply chain alertness is just as much dependent on coordination and collaboration as it drives them. Technologies such as IoT and smart sensors will allow for the real-time flow of information in the supply chain (Nagarajan et al., 2022), for which technological advancement of the supply chain members is very necessary. A key example of this can be seen in RFID tags and barcodes being used to track inventory and material flow in the chain.

Recommendation 2. Organizations need to monitor and control the flow of products as well as work on improving trust, information sharing, and collaboration both within and outside the supply chain.

Organizations that can ensure better visibility can maintain higher control over their products. The sharing of information amongst the supply chain members will lead to better collaboration, thus also improving the trust between the members (Mandal et al., 2016). All these aspects can come together to improve the supply chain's resilience by imparting knowledge and learning from one another. Learning is a critical part of supply chain resilience, and any organization can hope to increase its resilience using knowledge management and knowledge sharing that will include codification and sharing of the accumulated individual experiences to transfer them into organizational routines that can help prepare for potential future disruptions (Scholten et al., 2019). The experience and knowledge of existing employees can be used by employing BDA and AI to understand the challenges they faced and the decisions taken to introduce procedures for dealing with those challenges, along with the reasons and possible implications of those decisions. Another way to use the employees' experience is by creating a knowledge pool that can be used with advanced simulation technologies such as mixed reality and digital twins to create real-time life-like scenarios where managers can be trained to make better quantitatively supported decisions, inducing resilience.

Recommendation 3. Firms should invest resources to develop the technological capabilities of their long-term supply chain partners to improve their responsiveness and further their relations.

The organization information processing theory (OIPT) states that any firm wanting to sustain itself in a disruptive environment must evolve its information processing capacity to actively scan, interpret, and respond appropriately to continue its operations as usual (Bag et al., 2021). A technologically adept supply chain will have all the members at equally good information processing capability, thus ensuring that no technological weak links are exposed. A firm that will invest its resources to improve the responsiveness of its supply chain members will effectively gain their trust and cooperation, which will open communication between them, increasing collaboration. Technologies such as blockchain can also help improve the collaboration between the supply chain members to improve its responsiveness, making the supply chain resilient (Dubey et al., 2020). A higher level of collaboration amongst the members will ensure better visibility and disruption awareness in the supply chain, all of which can be attained by investing in better technologies, and in this way, I5.0 can help drive resilience in supply chain management.

## 5. Conclusion, Limitations, and Future Research Direction

The COVID-19 pandemic has showcased the shortcomings of supply chains worldwide, with every firm scattering to cope with the supply disruptions to maintain itself in the market. The government-imposed lockdowns, distance restrictions, and other factors provided us with insights into the need to become technologically capable to cope with the unpredictable disturbances and, in doing so, become resilient. This study answers this need by identifying and analyzing the criteria and CSFs of supply chain resilience and suggesting the integration of I5.0 technologies to optimize and improve the attainability of the CSFs to help the firms become resilient. The study adopts a novel hybrid methodology, which includes identifying the criteria and CSFs through a scoping literature search using the PRISMA 2020 statement. The CSFs were then validated using the Delphi technique with the help of expert opinions. The methodology's first stage consists of calculating the criteria weights using PF-AHP. After that, the analysis of CSFs begins with the use of m-TISM in the second stage and MICMAC analysis to develop a hierarchy model and divide the CSFs into four clusters according to their driving and dependence powers. In the third stage, PF-CoCoSo is applied to rank the CSFs in priority order with the help of the criteria weights found in the first stage. Finally, sensitivity analysis is done to check the robustness of the framework. The key highlight of the study is the identification of cost-effectiveness as the leading criteria and disruption awareness as the top priority of all CSFs. This effectively shows that the resilience of any organization is deeply intertwined with its profitability and resource expenditure and that by achieving resilient operations, a firm can boost its profit margins in the long run. Another integral takeaway is that firms have been dependent on their reactive capabilities for the most part when it comes to dealing with disruptions, but the results suggest otherwise and that the firms need to improve their proactive capabilities, which include disruption awareness, visibility, knowledge management and building redundancy to combat supply disruptions by detecting them early on and mitigating its effects, reducing the pressure on the reactive aspect of dealing with disruptions which can then be allocated to dealing with the recovery and the growth phase. Another noticeable feature is the interdependence of the priority-ranked CSFs from the results of PF-CoCoSo, which can also be seen from the m-TISM model (Figure 2). 'Disruption awareness' helps forecast supply disruptions so that the firms will get enough time to build a buffer to maintain operations and control the price by 'building redundancy.' A good stock capacity will allow firms to embrace 'agility' and allow them a free hand in handling resources to maintain continuous operations. Investing in I5.0 technologies that help support the prioritized CSFs will enable firms to become resilient by cost-effectively embracing technological advancement.

### *5.1 Limitations and Future Research Direction*

The current study has successfully identified and analyzed the criteria and CSFs of supply chain resilience and discussed the need for I5.0 technologies for attaining the said CSFs, highlighting the major I5.0 technologies that can help. However, as is the case with every research, this study also faces certain limitations even though the authors have done their best to avoid any major issues to keep the research results as true as possible. Some limitations of the research include the subjective nature of criteria identification and the number of experts taking part in the study. The number of experts in the study could be increased to generate marginally better results. The expert's judgment is also crucial for the analysis, and it was very challenging for the authors to get unbiased opinions. The authors have tried to limit any bias in data collection and analysis. However, there always remains a chance for biases to creep in.

Despite these limitations, the authors were able to use the results of the study to provide recommendations to the managers and future research areas for furthering the quality of the recommendations and understanding the nature of the impact of every CSF on organizational behavior. The effects of these CSFs can be studied concerning the RDT and RBV theories to improve the nature of the effect of using I5.0 technologies for attaining the CSFs to achieve supply chain resilience. The impacts of the criteria can also be studied individually to understand the reason for their weightage. Further research can be conducted to study the attainment of every individual CSF using I5.0 technologies.

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