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Investigating the interaction of factors for implementing additive manufacturing to build an antifragile supply chain: TISM-MICMAC approach

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Abstract

The outbreak of the Covid-19 pandemic has come across as an exogenous shock to the firms and their supply chains. It has led firms to rethink and rework their existing robust and resilient supply chains. The purpose of this study is to move beyond robustness and resilience and shift to an antifragile supply chain that sees disorder as an opportunity to learn and grow. In this study, various factors to attain an antifragile supply chain have been identified through literature review and experts' opinions. Using TISM-MICMAC, structural relationships among these factors have been developed, and, then the factors have been classified as drivers or dependents. The study reveals the importance of having proactive top management as a major driving power to build an antifragile supply chain. Development of a strategy for collaboration and innovation, development of a skilled workforce for technology adoption, and resource allocation for digitalization are some other factors with strong driving power. The novelty of the study lies in its effort to drive the attention of researchers and practitioners towards thinking beyond robustness and resilience and shifting towards antifragility. The study will help firms in strategic decision-making for the adoption of additive manufacturing technology to develop antifragility in the supply chain and save itself from negative consequences in the face of disruption.

Keywords Antifragile supply chain · Resilience · Additive manufacturing · TISM-MICMAC · Covid-19 · Pandemic

1 Introduction

In the recent past, firms have seen an increasing number of epidemic outbreaks (Baral et al. 2021). A whopping 1438 epidemics cases were reported by World Health Organization (WHO) from 2011 to 2018 (Hudecheck et al. 2020). The last decade alone has seen the outbreak of epidemics such as the Middle East respiratory syndrome / MERS-CoV in 2012, the Western African Ebola virus epidemic in 2013, and the Zika virus epidemic in 2015 among others.[1] The outbreak of Coronavirus (Covid-19) towards the end of 2019 was a rare catastrophic event. Later, on March 11, 2020, WHO classified the COVID-19 outbreak as a pandemic. The Covid-19 disaster constitutes a special case of pandemic outbreaks in terms of duration and intensity. It can be classified as a low-frequency-high-impact (LFHI) event. LFHI events cause a ripple effect that cascades through all the operations involved in a supply chain causing considerable adverse effects (Ivanov et al. 2014; Dolgui et al. 2018; Hosseini et al. 2019; Ivanov 2020; Kinra et al. 2020).

This pandemic has shocked supply chains across nations. It has exposed the vulnerabilities in the supply chains (El Baz and Ruel 2021). The supply chains that were otherwise considered a source of sustained competitive advantage (Barney 2012) turned out to be the Achilles heel of the companies negatively affecting the operations of more than 94%

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[1] https://www.who.int/emergencies/disease-outbreak-news/8

of Fortune's top 1000 companies (Fortune 2020). It has not only affected the supply side but demand ripples have also been observed (Guan et al. 2020; Sarkis 2021) both at global and local scales (Ivanov 2020). While demand deficiencies arose due to real or anticipated income risks and economic uncertainty, the world also saw a huge rise in demand for necessary items such as medical supplies and equipments including masks, gloves, oxygen cylinders, ventilators, PPEs (personal protective equipment), and sanitizers (Balleer et al. 2020; Bag et al. 2021a, b; Dubey et al. 2021). Similarly, with the closure of national and international borders, vehicle movement and international trade were interrupted. There was a shortage of labor and social distancing was supposed to be maintained (Gunessee and Subramanian 2020). These led to disruption in the flow of materials, information, and funds, and hence the entire supply chain was disrupted substantially (Chopra et al. 2021). The toilet paper shortage in the early days of the pandemic and the semiconductor shortage, a product with long lead times, for automakers are a few such examples.[2] The global supply chains struggled to deliver even the necessary items and their fragility and lack of operational agility became conspicuous (Mishra et al. 2021). Supply chains which were otherwise designed to be global and lean faced increased vulnerabilities in the current epidemic context. Globalization, offshoring, and lean systems were heavily scrutinized and looked at with mistrust since they increased the firms' exposure to disorder (El Baz and Ruel 2021).

The crisis has led to the researchers reflecting on the inadequacies of existing supply chain structures and risk management practices. The researchers have highlighted the need to build a fuller picture of the disruptions caused by the Covid-19 pandemic, its impact on the supply chain, and the response so far (Queiroz et al. 2020; Remko 2020). They also call for a robust and resilient supply chain in the event of future disruptions (Ivanov and Das 2020; Chowdhury et al. 2021). Resilience can be defined as "the ability of a supply chain to return to normal operating performance, within an acceptable period, after being disturbed" (Christopher and Peck 2004). The 68th session of the WHO Regional Committee for the Eastern Mediterranean also talks about building stronger systems and resilient communities.[3] By implementing several resilience-building strategies such as investing in flexibility, visibility, risk mitigation, or redundancy to name a few, these organizations strive to mitigate the immense pandemic crisis disruption in their supply chains (Chopra et al. 2021).

Digitalization of the supply chain has emerged as a resilience-building strategy in the recent past. Technological advancements and digitalization (Hald and Coslugeanu 2021) have played a substantial role in accelerating supply chain resilience. Additive manufacturing (AM) methods, such as 3-D printing technology can prove an effective way to digitalize manufacturing and supply chain operations. AM involves layer upon layer joining of the materials to make the final product from a 3D model data (ASTM F2792-12 2012). This is the stark opposite of what traditional subtractive manufacturing does. AM remarkably surpasses the traditional manufacturing methods and has the potential to become the norm over the decades to come (Attaran 2017). The popularity of AM has grown considerably in the last decade and it is now being pursued by many researchers (Achillas et al. 2017). With new technologies and new materials coming into play, there has been rampant growth in the application of AM across various manufacturing industries (Gardan 2016; Huang et al. 2021a, b) which includes sectors such as automotive (Muhammad et al. 2021), aerospace (Kemsaram and Maley 2019), medical (Choudhary et al. 2021; Patel and Gohil 2021), and electronics (Ghobadian et al. 2020). During the pandemic, AM technologies have been used to quickly meet the increased demand for medical equipment and kits such as ventilators, PPEs, hands-free door openers, and face shields (Iyengar et al. 2020; Novak and Loy 2020). Thus, AM technologies can be leveraged to build a robust and resilient supply chain.

Several articles in the extant literature have studied the impact of catastrophes and pandemics on the supply chain (Fonseca and Azevedo 2020; Okorie et al. 2020; Sharma et al. 2020), and some have suggested resilience and robustness as a means to tackle supply chain disruption. However, resilience talks only about the bouncing back of supply chains. It fails to recognize the need to learn and grow from such disruptions. Hence, the need of the hour is to build an antifragile supply chain. While a resilient supply chain aims at absorbing shocks, an antifragile supply chain sees these shocks as an opportunity to get stronger and better. An antifragile supply chain does not only respond to disruption but also thrives in it (Taleb 2012). While resilient supply chains have been extensively discussed, very few articles discuss an antifragile supply chain as a response to the disruption caused by pandemics. Größler (2020) has explored the consequences of antifragility on supply chain behaviour and performance through simulation. Jaaron and Backhouse (2014) explored the impact of the application of systems approach in service organizations to build an antifragile system that flourishes in disruption. Nikookar et al. (2021) have built on Taleb's concept of antifragility and have introduced the concept in the purchasing and supply chain management discipline. They have briefly discussed some directions leading to an antifragile supply chain and

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[2] https://www.whitehouse.gov/cea/written-materials/2021/06/17/why-the-pandemic-has-disrupted-supply-chains/

[3] http://www.emro.who.int/pandemic-epidemic-diseases/outbreaks/outbreaks-archive.html

have suggested the nexus between antifragility and Industry 4.0 technologies as a scope for future research. This study discusses Additive manufacturing applications to build an antifragile supply chain. AM reduces the lead time, offers huge flexibility, shortens the time to market (Engelseth et al. 2021), and helps to achieve environmental sustainability (Afshari et al. 2019). The decentralized supply chain promoted by AM helps to locate the manufacturing facility closer to the customer (Rinaldi et al. 2021a, b). With operational and technological innovations, AM can also be used to achieve high-volume production output (Huang et al. 2021a, b). The digital inventory that can be held in AM and the possibility of having multiple iterations before actually printing the product make it preferable over the conventional manufacturing technologies (Engelseth et al., 2021). Thus, AM enhances the overall supply chain flexibility and performance (Delic and Eyers 2020). It helps in achieving supply chain agility (Ohmori 2021), and increases the supply chain responsiveness (Boer et al. 2020) which are important factors to thrive during a disruption. To the best of the authors' knowledge, this is by far the only study that exclusively talks about leveraging additive manufacturing capabilities as a strategy to build an antifragile supply chain. Consequently, this study seeks to achieve the following research objectives:

RO1 To identify the factors affecting the implementation of additive manufacturing technologies to build an antifragile supply chain during disruption.

RO2 To develop a structural relationship framework for the identified factors that affect the implementation of additive manufacturing technologies to build an antifragile supply chain during disruption.

RO3 To categorize and analyze these factors based on driving and dependence power.

For the first objective, a literature review is conducted to derive the factors affecting AM implementation from an academic perspective. Post this, the industry perspective is captured using experts' opinions. For the second and third objectives, total interpretive structural modeling (TISM) and Matrice d'Impacts Croisés Multiplication Appliqués à un Classement (MICMAC) analysis are used to establish the structural relationships among AM implementation factors and to categorize these factors based on driving and dependence power respectively. While several studies have been performed on additive manufacturing techniques, these are mostly qualitative, and very few studies have used multi-criteria decision-making (MCDM) techniques to categorize and analyze the factors. This study uses TISM to build a structural framework that would help in better understanding the relationship between the factors. Few studies in the past, have studied the factors for AM implementation using ISM. Sonar et al. (2020) have used ISM to understand the factors that influence AM implementation in the Indian manufacturing sector. Dwivedi et al. (2017) have used fuzzy-ISM to analyze the barriers to implement AM in the Indian automotive sector. Shukla et al. (2018) have used ISM to understand the barriers to implementing AM for mass customization. Choudhary et al. (2021) analyzed the barriers to AM adoption in the medical sector. To the best of the authors' knowledge, this is by far the first study utilizing the approach of TISM to explore the structural relationship between the factors affecting the implementation of additive manufacturing technologies to build an antifragile supply chain during disruption.

The remaining part of the paper is structured as follows. In the Sect. 2, we discuss related literature and provide the theoretical foundation for the paper. Following this, the research methodology is described. In Sect. 3, we then present the TISM model for understanding the critical success factors for AM implementation to build an antifragile supply chain. In Sect. 4, the MICMAC analysis is presented and then in Sect. 5, we discuss the results of the research, managerial and practical implications of the study. Finally, in Sect. 6, we conclude by summarizing the results, discussing the limitations of our study, and providing some areas for future research.

2 Literature review for identification of factors

In this study, first, a thorough review of the extant literature was done to find the critical success factors to build an antifragile supply chain (SC). For this purpose, literature on additive manufacturing and the ones discussing antifragility and resilience building in a supply chain were reviewed.

2.1 Pilot search and article selection criteria

In the first phase, a pilot search was conducted to gain an idea of the ongoing research in the field. Scopus was used as the database to search for articles on the two topics. Scopus is one of the largest multidisciplinary databases with citation indexing. It has a broader and more robust cover-to-cover indexing policy than Web of Science and offers the best choice amongst the multidisciplinary databases with citation indexing (Norris and Oppenheim 2007). Scopus has better coverage as compared to Web of Science (Martín-martín et al. 2019; Mongeon and Paul-Hus 2016). Comerio and Strozzi (2019), who have collected preliminary data for their study from Scopus, highlight that Scopus has 60% more content coverage than Web of Science. Gupta et al. (2019) used a similar approach in their study where Scopus was used as the database. The importance

Table 1 Search syntax*

Database and search topic	Search syntax	Records obtained
Scopus - AM	TITLE-ABS-KEY (“Supply chain” AND (“Additive manufacturing” OR “3D printing” OR “3DP”)) AND (LIMIT-TO (SUBJAREA, “BUSI”)) AND (LIMIT-TO (LANGUAGE, “English”))	173
Scopus - Resilient supply chain	TITLE-ABS-KEY (“supply chain” AND (“resilient” OR “resilience” OR “robust") AND ("Covid" OR "covid-19" OR "pandemic")) AND (LIMIT-TO (SUBJAREA, "BUSI")) AND (LIMIT-TO (PUBYEAR 2022) OR LIMIT-TO (PUBYEAR 2021) OR LIMIT-TO (PUBYEAR 2020)) AND (LIMIT-TO (LANGUAGE, "English"))	200
Scopus - Antifragile supply chain	TITLE-ABS-KEY (("antifragile" OR "Anti fragile" OR "anti-fragile" OR "antifragility") AND ("supply chain" OR "operations")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "DECI"))	5

(*Last accessed on 06 January 2022)

of using the right set of keywords for literature search has been highlighted by Rowley and Slack (2004). For this purpose, the keywords such as ‘Additive manufacturing’, ‘3D printing’, and ‘supply chain’ were included in the search string. The reason for including supply chain along with additive manufacturing was to get an output where the articles would be discussing additive manufacturing from the supply chain perspective because several studies in AM have also been done on manufacturing part in the engineering domain which was not to be a part of the scope of this study. The search syntax for the keywords has been discussed in Table 1.

As discussed in the previous sections, antifragility is a novel concept and is unexplored. The search syntax for an antifragile supply chain also reveals the same. Thus, this provides us with a very good opportunity to explore the field further. In the next stage, the articles written in English were only considered and the subject area was limited to Business management. For literature on resilient supply chain, the study focussed mostly on publications from 2020 and after. This is because ever since the outbreak of the Covid-19 pandemic, there have been numerous studies done on building resilience into the supply chain. However, some studies discussing resilience-building strategies in the supply chain that were published before 2020 were also identified through cross-referencing and included in the study. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were followed for article selection and inclusion. The above Boolean search resulted in 378 articles and another 24 articles were included through snowballing and cross-reference. These articles were then uploaded in Zotero software where the duplicates were removed, leaving us with 363 documents. Further, an abstract search for these articles was done and another 211 documents were excluded. In the end, after the full-text screening, 105 documents were retained for this study. The PRISMA flow diagram for study selection and exclusion has been shown in Fig. 1.

2.2 Identification of factors

The ever-changing business environment, business scenarios, and such a high level of uncertainties during a disruption such as the Covid-19 pandemic cause sudden and huge changes in customer demand. The firms are cautiously looking forward to moving towards technological innovations and a resilient, robust, and antifragile supply chain. The firms must build dynamic capabilities to address such disruptions to the supply chain in a timely fashion to avoid negative consequences on firms’ overall performance (Dubey et al. 2019).

Introduced in the 1980s, Additive Manufacturing (AM), also known as 3D printing or rapid manufacturing has grown in popularity by benefitting manufacturers who want to produce less quantity of complex parts. The easy availability and accessibility of tools required in the additive manufacturing process is enabling firms to adopt this technology. With need basis printing and reduction in inventories, AM seems to be having a bright future. In this study, we have aimed to introduce AM as an implementation strategy to build an antifragile supply chain. An antifragile supply chain gains from disorder. They get stronger by being exposed to intentional randomness, similar to the human immune system (Nikookar et al. 2021). An article in Financial Times (Ft.com 2020) also discusses how firms need to move beyond robustness and resilience and aim for antifragility.

In the next section we have discussed the 19 factors leading to an antifragile supply chain identified through literature review:

i. Development of skilled workforce for technology adoption

   Afshari et al. (2019) highlight the need for highly skilled workers for AM, who would facilitate the design process, and who could operate the AM machines. They also discuss how skilled workers can

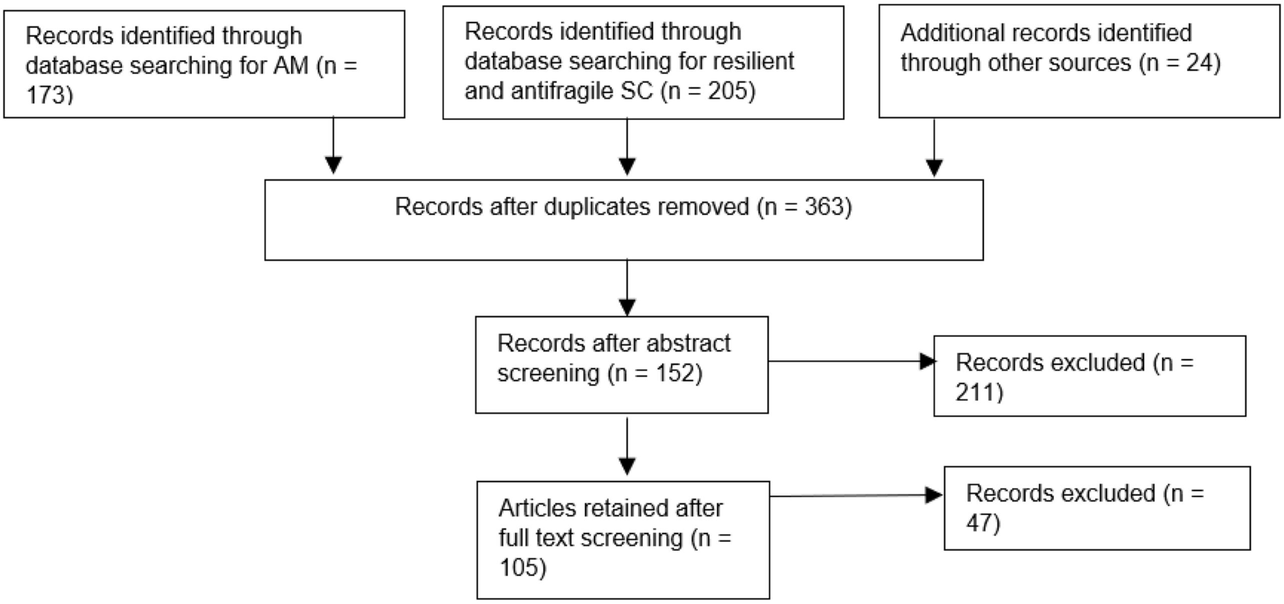

Fig. 1 PRISMA flow diagram for study selection criteria

affect profitability while implementing novel paradigms, such as AM. Despeisse and Minshall (2017) discuss how the lack of skills and education prevents the firms from adopting AM technology. Technical and managerial skills are two important aspects of human resources and these skills need to be developed over time (Gupta and George 2016). It is important to plan for the resource supply chain strategy which involves selecting the critical workforce for the firm, one which will have the capability to handle disruptions in the supply chain. The firm should be able to handle those resources under any circumstances (Sharma et al. 2020).

ii. Cost-effective design and manufacturing

Researchers have suggested 3-D printing techniques, as a solution to help companies design and manufacture products quickly (Novak and Loy 2020). In the recent past, owing to the advancement in technologies, the price of 3D printers has gone down making it even more feasible for firms to implement 3D printing (Attaran 2017). Moreover, a decentralized supply chain facilitated by AM offers a better solution in terms of holding stock, and in general, on supply chain costs as compared to traditional manufacturing (Nagarajan et al. 2018). AM also shortens the supply chain which leads to a shorter cash-to-cash cycle. With AM machines there are no costly setups, and so production of small batches becomes economical (Pour et al. 2016). On-demand manufacturing eliminates the need for stockpiling inventories.

iii. Reduction in manufacturing lead time

Additive manufacturing supports mass customization at low cost and without a lengthy delivery time (Pereira et al. 2019). AM, by its additive capabilities, reduces the number of parts that need to be produced, procured, or assembled. This considerably brings down the assembly time leading to shorter manufacturing lead times (Rogers et al. 2016; Despeisse et al. 2017). The faster production process coupled with a simple supply chain brings down the supply chain lead time (SCLT). An SCLT reduction of up to 60% has been estimated by switching from conventional to additive manufacturing (Rinaldi et al. 2021a, b).

iv. Environmental sustainability

AM has the potential to substantially reduce material consumption and wastage during manufacturing thus reducing the emission of CO_2. It minimizes the need for logistics, thus, CO_2 emissions associated with transport activities are reduced (Rinaldi et al. 2021a, b). It also facilitates an extended product life which is achieved through technical approaches such as repair, remanufacture, and refurbishment (Ford and Despeisse 2016; Boer et al. 2020). The strength and durability of the product are enhanced. There are 3D printed concrete-based houses which can withstand 8.0 Richter scale earthquakes (Ghaffar et al. 2018). Kumar et al. (2020) discuss how AM technologies can be utilized to build sustainability in the supply chain. Mukherjee et al. (2021) argue that to develop supply chain capabilities, it is important to support sustainable practices.

v. Development of strategy for collaboration and innovation

A synchronized system would lead to intelligent workflows which will improve efficiencies across the supply chain. With this, the firms will be able to quickly intuit the changes in the environment and respond with the help of intelligent workflows by processing any delivery changes or responding to a new customer request with minimum hassle and error (Oyekan et al. 2017; Zhong et al. 2017). To perform efficiently, a supply chain depends on close collaboration across various supply chain partners (Bag et al. 2021c). Close collaboration with SC partners is also required for efficiently mitigating the risk factors in a supply chain before a disruptive event occurs or after the event has unfolded (Fan and Stevenson 2018). SC collaboration will help the firms in achieving end-to-end visibility, understanding associated complexities, and reducing the vulnerabilities in the supply chain. Also, technological and operational innovation could help firms in achieving competitive advantage and catering to rapid demand changes (Huang et al. 2021a, b).

vi. Manufacturing repurposing

Manufacturing repurposing has been identified as critical to manufacturing life-saving products. Repurposing is a quick response solution to cater to the manufacture of essential items such as PPEs, diagnostic equipment, and clinical care equipment.[4] However, it is considered a temporary strategy and can be challenging and expensive to implement. It would require the employees to be trained to handle such temporary repurposing thus making employee skills and know-hows a crucial enabler (Okorie et al. 2020).

vii. Effective additive manufacturing processes

Additive manufacturing can easily be considered a revolution in the field of manufacturing technology (Oettmeier and Hofmann 2016). It opens new avenues for business firms that intend to improve their manufacturing efficiency. Some studies consider AM a powerful tool to simplify the supply chain in many ways. The popularity of AM has grown considerably in the last decade and it is now being pursued by many researchers who study the advantages it offers as compared to traditional manufacturing (Achillas et al. 2017). With new technologies and new materials coming into play, there has been rampant growth in the application of AM across various manufacturing industries (Gardan 2016) which includes sectors such as automotive, aerospace, medical, and electronics (Ghobadian et al. 2020).

viii. Supply chain risk management

SC risk management practices are aimed at reducing the supply chain vulnerabilities and mitigating the impacts of the disruptions (Ho et al. 2015). This involves four interconnected processes: risk identification, risk assessment, risk mitigation, and risk control (Fan and Stevenson 2018). AM technologies have been known to lead to supply chain integration and risk management through its digital nature, where the design can be easily transferred to a different location and printed in case of disruptions faced at one manufacturing location (Durach et al. 2017). The design and volume changes can be easily accommodated which helps in moving the order decoupling point closer to the customer (Tuck et al. 2007). This provides agility in case of supply chain disruption. A diversified supply chain reduces the firms' dependence on a few suppliers, provides supply chain flexibility and creates agility that helps reconfigure the supply chain whenever required.

ix. Effective inventory management

Additive manufacturing efficiently changes the supply chain configuration, thus achieving a reduction in safety inventory which helps in cutting down the inventory holding costs significantly (Cestana et al. 2019). In additive manufacturing, there are no held-up costs and risk of scrapping the unsold finished goods inventories. Instead, firms only hold digital 3D data in stock (Berman 2012). The on-demand manufacturing capability of AM eliminates the need for stockpiling inventories (Hedenstierna et al. 2019). Direct digital manufacturing might currently lag traditional manufacturing methods but with technological and operational innovations, it will very soon question the established practices of inventory management (Holmström et al. 2016).

x. Proactive top management

Top management commitment is an important factor for the implementation of AM to build a resilient supply chain (Sonar et al. 2020). A proactive decision-maker would plan for rapid global crisis detection and response systems which will eventually lead to enhanced competitiveness for the firm (Singh et al. 2007; Dwivedi et al. 2017). Ivanov and Das (2020) have also highlighted the need for proactive top management who would be responsible for mapping the supply chain and synchronization of strategic processes such as creating flexible redundancies in the supply chain. These activities would enhance supply chain collaboration (Bag et al. 2021d) and make the SC networks less sensitive to external uncertainties.

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[4] https://www.unido.org/news/covid-19-critical-supplies-manufacturing-repurposing-challenge

Devi et al. (2020) highlight the importance of proactive decision-making by top management who have the sole responsibility to plan, strategize and implement digitalization of the supply chain.

xi. Supply chain redesigns

The supply chain redesign can be considered in two aspects: multi-sourcing and reinforced e-commerce capabilities. Multi sourcing involves procuring the raw materials from multiple suppliers instead of relying on a single supplier. This would result in building redundancy across suppliers.[5] Resorting to e-commerce and moving from Business to Business (B2B) to Business to Consumer (B2C) are other ways of SC redesign that enable building resilience. Many firms, with physical stores closed, have transitioned to e-commerce (Barriball et al. 2020).

xii. Efficient information sharing process

A resilient supply chain requires firms to collect data on their critical processes, flows, and partners so that the necessary optimization steps can be taken when required (El Baz and Ruel 2021). Another means to prevent supply chain disruption is to time the closing and opening of the facilities at different SC echelons. This can be done only when necessary technologies have been installed for real-time information sharing which enhances supply chain visibility (Routroy et al. 2018). The technologies enable real-time tracking of the goods and with digitalization, this huge volume of information can be analyzed and used for process improvements (Zhong et al. 2017). For this purpose, RFID and GPS systems could be utilized. Also, this would help in pre-emptive breakdown and maintenance of the machinery (Sanders et al. 2016). Converting data into meaningful information will help the firms in predicting disruptions and preparing necessary actions and this information sharing leads to better collaboration, thus enhancing the overall supply chain performance (Baah et al. 2021). Dubey et al. (2019) have discussed how information-sharing positively impacts supply chain visibility, which in turn impacts supply chain resilience.

xiii. Distributed manufacturing system

Decentralization of manufacturing capacity and production in smaller batches are important aspects for building future supply chains (Fonseca and Azevedo 2020). The establishment of geographically-dispersed manufacturing facilities with the necessary logistical supports is considered effective as a pro-active readiness strategy (Shokrani et al. 2020). For this purpose, the firms will also need to redesign their logistics systems and switch to faster delivery modes (Chowdhury et al. 2021). AM facilitates a shorter and simpler supply chain. It reduces the number of raw material suppliers required by dint of its additive properties. It supports decentralized manufacturing where the technology could potentially reduce the need for logistics as designs could be transferred digitally (Luomaranta and Martinsuo 2020). Flexibility to produce different products in a single run, tooling freedom, as well as the possibility of making products without having molds, are some other benefits of AM implementation (Pour et al. 2016). It also supports easy manufacturing of products that fall under the Mass Complexity category, where parts exhibit complex geometries (Pereira et al. 2019). Smaller batch size production is possible due to AM capabilities which decreases the dependency on forecasting (Bogue 2013; Bogers et al. 2016).

xiv. Resource allocation for digitalization

Gupta and George (2016) have proposed seven resources critical to an organization to build digital capabilities. They discuss tangible resources such as data, technology, time, and investments, human resources such as managerial and technical skills, and intangible resources such as data-driven culture and the intensity of organizational learning. Integrating the technologies with the supply chain improves the overall operational efficiency of the supply chain and eliminates wastes and non-value-added tasks (Raji et al. 2021). Technology deployment will also enable the firms in monitoring their supply partners' actions (Sharma et al. 2020). Bag et al. (2021c) in their study, elucidate how tangible resources and workforce skills drive technological enablement.

xv. Antifragile supply chain

The COVID-19 crisis has revealed fragility and exposed the global supply chains' vulnerability and low resilience (Delic et al. 2019). Operational and supply chain resilience has three aspects, namely preparedness, response, and recovery. Preparedness corresponds to taking a proactive measure for unforeseen disruptions. Responsiveness corresponds to acting quickly along with the other supply chain partners to minimize the immediate impacts. For recovery, the aim is to return to the original or even better form after the disruption (Chowdhury and Quaddus 2016). An antifragile supply chain goes beyond a robust and resilient supply chain and thrives in disorder. To gain antifragility, a supply chain needs to develop optionality, create redundancy, weaken the link between the nodes, encourage eustress, adopt a barbell strategy, allow systems to fail fast, learn from the failures, and

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[5] https://www.mckinsey.com/business-functions/operations/our-insights/risk-resilience-and-rebalancing-in-global-value-chains

conduct trial and error, effectuation, and swarming. These help the supply chain in detecting vulnerabilities early, learning quickly, and gaining from disorder (Nikookar et al. 2021). Antifragility provides a complete alternative to deal with future uncertainties (Derbyshire and Wright 2014).

xvi. Rapid market responsiveness

AM offers flexibility which enables manufacturers to create an optimal design for lean production (Chekurov et al. 2018; Devi et al. 2020). With AM, customer demand can be met quickly, and this leads to improvement in the quality of care and aftermarket services. While modification of design costs significantly and also causes time delays in a traditional manufacturing setup, additive manufacturing facilitates the production of multiple versions of a single product through digital 3D mode, that too in a cost-effective manner (Rogers et al. 2016; Jimo et al. 2019).

xvii. Integrated manufacturing processes/operations

Integration of manufacturing processes is a major requirement for achieving the global manufacturing paradigm (Valilai and Houshmand 2015). AM encourages a distributed manufacturing system thus making data management a crucial task. This requires the integration of autogenous, scattered, and unorganized data sources into a single data source. Also, to reduce the build time, improve geometry quality and reduce the geometrical errors in the production process, global integration through AM paradigm becomes imperative (Jin et al. 2013). The digital nature of AM promotes the integration of various processes and functions in a supply chain where improving data flow becomes very important (Delic et al. 2019). By adopting the integrated and coordinated approach, additive manufacturing enhances firm competitiveness and helps achieve sustainability targets (Gebler et al. 2014; Dircksen and Feldmann 2020).

xviii. Effective knowledge management process

Proactive top-level management would ensure accurate mapping of the supply chain beyond the first or second supply tiers (Ivanov and Rozhkov 2020). Nissan has developed a supply chain resilience program that incorporates supply chain mapping and visibility. This would protect its supply chain in case of disruptions by helping the firms to formulate node or supplier-specific strategies (Ivanov and Dolgui 2021). The firms need to assess how much they are dependent on other countries and what critical technologies, critical resources, and manufacturing capacity they want to retain. After the pandemic, several countries have started re-evaluating their supply chains and reducing their dependency on other countries to be resilient. Even if a firm decides to outsource products from overseas, it will still need to strike a balance between domestic production and international trade to reduce vulnerability (Deaton and Deaton 2020). Flexible manufacturing system technologies such as additive manufacturing and robotics can localize production capabilities (Sarkis 2021). The collaborative environment and the sharing of knowledge provided by AM aim to expand the strategic scope, maximizing the supply chain surplus (Shah et al. 2017; Equbal et al. 2021).

xix. Design freedom and customisability

The need of the hour is to design products that incorporate component switching options. This would enable the firm to procure the raw materials or components from other suppliers where the disruption has not yet occurred (Ivanov and Das 2020). With AM, any design changes can be easily made digitally and multiple iterations could be tried without any cost penalties (Engelseth et al. 2021). It also substantially reduces the product repair time and provides an opportunity to modify the repaired components to the latest design. Furthermore, with the innovation of smaller 3D printing machines, it is now possible for consumers to print their parts for fixing their purchased products (Attaran 2017). AM also enables customers to co-design products that can perfectly fit their demands and ambitions (Ghaffar et al. 2018).

3 Research methodology

Once the factors were identified, using expert opinion initial reachability matrix was built and, in the end, total interpretative structural modeling (TISM) was used to highlight the interdependence between these factors. Furthermore, cross-impact matrix multiplication (MICMAC) was used to determine each factor's driving and dependence power.

3.1 Total interpretive structural modeling (TISM) and model development

Interpretive Structural Modeling (ISM) was first developed by J. Warfield in 1974 (Warfield 1974) and is an adaptation of paired comparison approach (Haleem et al. 2012). ISM methodology helps in addressing complex issues and aims to provide order and direction to the complex relationships among the elements in a system. The application of ISM helps the top-level management reassess their perceived priorities of the factors and understand the linkages between the factors (Singh 2015). Singh and Gupta (2020) used ISM to develop a structural relationship among sustainable maintenance system factors from a strategic perspective. Even though ISM serves to provide solutions to critical management issues through the development of hierarchies among the elements, it has several limitations. First, the correct interpretation of how the direct linkages between the elements operate is not explained by ISM. Second, it fails to explain the transitive links and causality of the linkage between building blocks of the ISM (Sushil 2012). Thus, TISM was developed which provides an interpretation of both nodes and links. TISM is the extension of ISM and can provide a better explanatory framework with important transitive links (Behl et al. 2018). While ISM helps to understand the 'what' and 'how' of a research study, TISM helps in answering the 'why' (Hasan et al. 2019a, b).

TISM is an innovative technique used by many researchers across various fields. Yadav and Sushil (2014) used TISM to model the performance factors in the Indian Telecomm. Service Industry. Dubey et al. (2015) employed TISM to study the association among various enablers for sustainable manufacturing. Singh and Sushil (2013) have used TISM in the airline industry, Bag (2016) employed TISM in the green procurement sector and Mahajan et al. (2016) used TISM to analyze the interrelations among challenges of management education in India. Since this study intends to model the critical success factors for AM implementation to build an antifragile supply chain, TISM was chosen as the method to accomplish the objective. Table 2 discusses some of the recent papers that have successfully applied TISM in their studies. TISM flowchart illustrating all the steps in the TISM-MICAMC process has been shown in Fig. 2.

3.2 Questionnaire development and data collection

After identification of a total of 19 critical success factors from the literature, the second phase was to focus on the selection of experts who would be willing to participate in the study. Through an internet search, companies that have applied AM technologies were identified and contacted for participation. Also, a few academicians (subject matter experts) were identified and contacted. We received participation confirmation from 7 experts across industry and academia. Murry and Hammons (1995) and Novakowski and Wellar (2008) have suggested that a sample size between 5 and 15 could be taken to get quality results in cases of high heterogeneity of the panel of experts. Thus, a sample size of 7 experts used in this study is adequate. Details of the experts who participated in the study have been mentioned in Table 3.

Delphi method was used to finalize the factors and build the structural self-interaction matrix (SSIM). The Delphi method was proposed by Dalkey and Helmer (1963) and aims at getting consensus from a panel of experts while providing anonymity to the participants. To determine the critical success factors, a questionnaire was developed and shared with the experts asking for their opinion on the importance of those 19 factors identified from literature on a Likert scale of 1 to 5 (1 being strongly disagreed and 5 being strongly agreed). The experts were also asked to add to the list, any factor which they found missing. The views and opinions of the experts were then compiled and, in the end, resulted in 16 critical success factors being a part of our study. For this purpose, the factors for which the mean score was greater than 3 were only considered for the study. Thus, after the experts' opinion, the factors 'Supply chain redesign' 'Manufacturing repurposing' and 'Environmental sustainability' were dropped. Then the response was collected from the participants for the SSIM based on the Delphi approach where the output from the previous round was compiled and sent to the participants for review. The list of the critical success factors for AM implementation to build an antifragile supply chain has been mentioned in Table 4.

4 Results and data analysis

Different steps of TISM that were followed to analyze results are mentioned in the following sections.

4.1 Structural self-interaction matrix

After finalizing the 16 critical success factors, the next step was to establish a contextual relationship among the factors. This was done based on the pair of factors that were identified. Thus, a pairwise comparison matrix (SSIM) for the 16 critical success factors was developed with the help of expert opinion. To establish a relationship between any two factors, four symbols have been used which denote the direction of the relationship between the factors i and j (where $i < j$). The symbols are as given below:

- V – Factor i will lead to parameter j
- A – Factor j will lead to parameter i
- X – Factors i and j will lead to each other
- O – Factors i and j are unrelated

In the SSIM (Table 5), we can see the use of the symbols V, A, X, and O. Here, factor 1 leads to factor 15 (V). Factor 14 leads to factor 3 (A). Factors 6 and 14 lead to each other (X). Factors 2 and 6 are unrelated (O). The structural self-interaction matrix (SSIM) has been displayed in Table 5.

4.2 Reachability matrix

In the next step, the SSIM was converted into a binary matrix, also known as the initial reachability matrix. This was done by substituting *V*, *A*, *X*, and *O* with 1 and 0 as per the case. The substitution of 1 s and 0 s were done based on the following rules (Singh et al. 2018):

Table 2 List of studies that implemented TISM

Sl. No.	Objective of Study	Key finding	Journal	References
1	To identify and analyze critical success factors that may improve the efficiency of a digital supply chain	TISM explained the importance of redesigning the organization to build an agile supply chain	Benchmarking	Choudhury et al. 2021
2	To identify and explain the relationships between the technology-related factors that lead to innovations in organizations	Six factors were identified. Top management support and technological infrastructure of an organization have a greater impact on innovation	Benchmarking	Rajan et al. 2021
3	To identify barriers in the adoption of blockchain technology in the Indian health-care industry	Fifteen barriers were identified. TISM was applied to develop a multilevel structure for the barriers. Low awareness related to legal issues and low support from a high level of management had the highest impact	Journal of Global Operations and Strategic Sourcing	Sharma and Joshi 2021
4	To prioritize and analyze lean barriers for successful lean implementation	Insufficient management time, insufficient supervisory skills, and insufficient senior management skills had the highest driving power and lowest dependence	International Journal of Lean Six Sigma	Chaple et al. 2021
5	To identify and analyze agri-food supply chain risks	Sixteen risk factors were identified. Weather-related and political risks have the highest driving power	International Journal of Production Research	Zhao et al. 2020
6	To study the challenges in the adoption of Procurement 4.0	High and unclear investments and organizational inertia which is present in established and structured firms are found to be a deterrent	Benchmarking	Joseph Jerome et al. 2021
7	To explore the barriers of Health 4.0 application in the healthcare sector in India	Fifteen barriers were identified. Lack of top management support, exclusive and skilled workforce requirement, inadequate maintenance support systems, and political support were found to be the major barriers	Operations Management Research	Ajmera and Jain 2019
8	To identify the big data analytics-based enablers of supply chain capabilities and competitiveness of firms	IT infrastructure, leadership commitment, people skills, and financial support had the highest impact	Journal of Enterprise Information Management	Bamel and Bamel 2020
9	To identify and prioritize various growth-accelerating factors in the Indian automotive industry	Rising income and a large young population, greater availability of credit and financing options, and availability of low-cost technical workforce were found to be the main driving factors in the growth of the automotive industry in India	International Journal of Productivity and Performance Management	Meena et al. 2021
10	To find critical success factors in developing intelligent autonomous systems by integrating artificial intelligence with robotics	Eight significant factors, that is, emerging economy multinational enterprises (EMNEs), governance, utility, manpower, capital, software, data, and hardware, were identified as the most important factors in integrating AI with robotics in India	Digital Policy, Regulation, and Governance	Mir et al. 2020

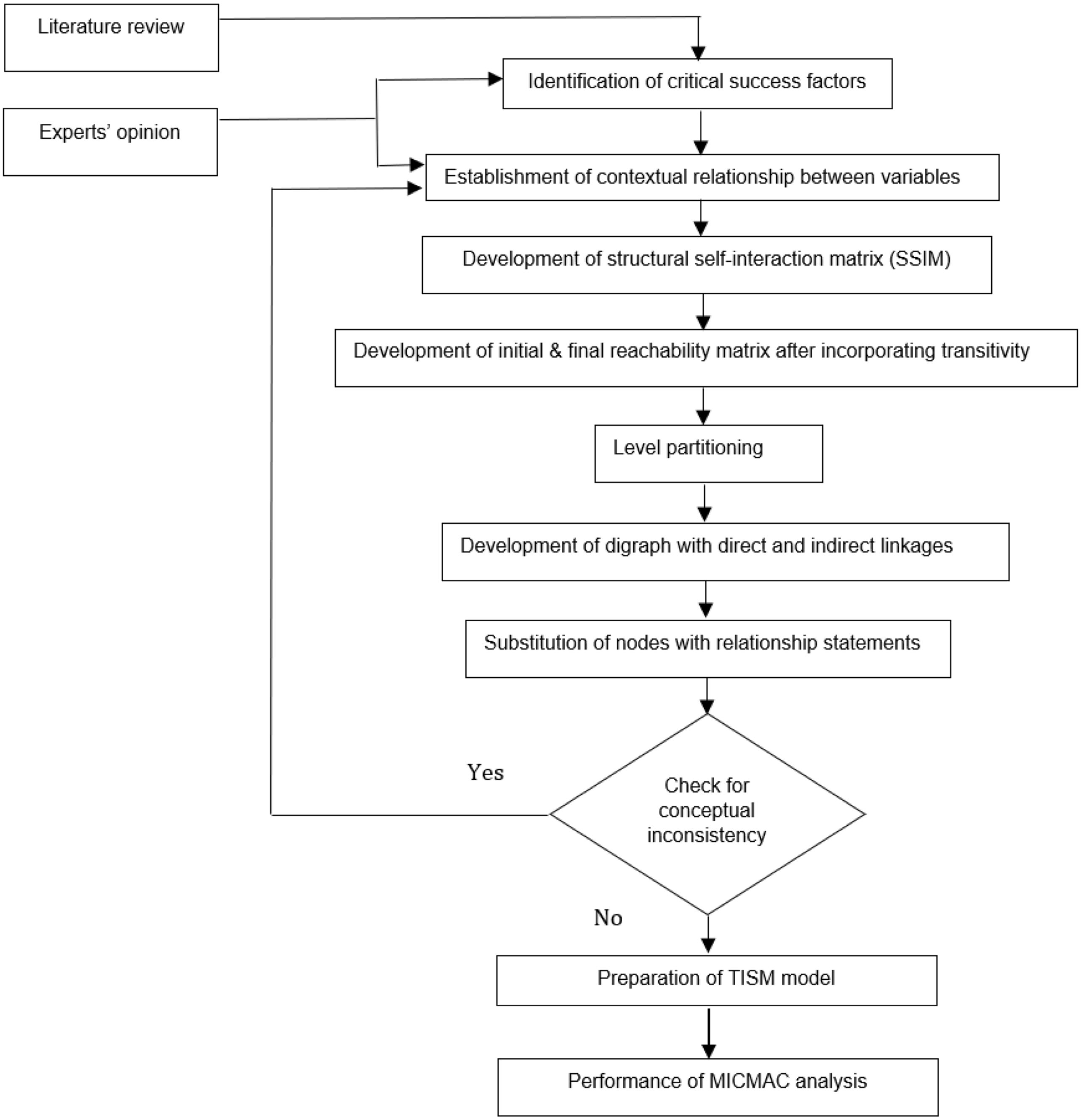

Fig. 2 TISM flowchart

- If the (*i*, *j*) cell in the SSIM is *V*, the (*i*, *j*) entry in the reachability matrix becomes 1 and the (*j*, *i*) entry becomes 0.
- If the (*i*, *j*) entry in the SSIM is *A*, the (*i*, *j*) entry in the reachability matrix becomes 0 and the (*j*, *i*) entry becomes 1.
- If the (*i*, *j*) entry in the SSIM is *X*, the (*i*, *j*) entry in the reachability matrix becomes 1 and the (*j*, *i*) entry also becomes 1.
- If the (*i*, *j*) entry in the SSIM is *O*, the (*i*, *j*) entry in the reachability matrix becomes 0 and the (*j*, *i*) entry also becomes 0

The above rules have been followed to form the initial reachability matrix as shown in Table 6.

After the formation of the initial feasibility matrix, the next step is to check for transitivity. Transitivity can be explained with the following example: if element A relates

Table 3 Experts' profile

Sl. No	Expert's profile	Industry	Experience in years
1	Technical lead	Service provider	12
2	Assistant manager	Automotive	8
3	Senior design engineer	Jewelry and dental	7
4	Academician	Education	6
5	Academician	Education	10
6	Business development manager	Service provider	7
7	Senior product engineer	Consumer products	12

to element B and element B relates to element C, then transitivity implies that element A should relate to element C. It also helps in maintaining conceptual consistency. After incorporating the transitivity, the final reachability matrix is prepared as shown in Table 7. The * marks represent transitivity. We have also calculated the driving power and dependence for each factor in Table 7. The driving power is the total number of variables (including itself), that the factor might help to achieve. On the other hand, dependence is the total number of variables (including itself), that might help in achieving the factor. These driving power and dependencies will be utilized at a later stage while we classify the factors into four groups of autonomous, dependent, linkage, and drivers.

4.3 Level partitions

The final reachability matrix is then divided into different levels for each factor based on reachability and antecedent sets through a series of iterations called level partitions. The reachability set for each factor comprises of the element itself and other elements which it might help in achieving, whereas the antecedent set for each factor comprises of the element itself and other elements, which might help in achieving it. Then, the intersection of these sets is derived for all factors. The factors for which the reachability and intersection sets are the same are the

Table 4 Critical success factors for AM implementation to build an antifragile SC

Sl. No.	Factors	References
1	Development of skilled workforce for technology adoption	Gupta and George 2016; Despeisse and Minshall 2017; Afshari et al. 2019; Sharma et al. 2020
2	Cost-effective design and manufacturing	Pour et al. 2016; Attaran 2017; Nagarajan et al. 2018; Novak and Loy 2020
3	Reduction in manufacturing lead time	Rogers et al. 2016; Despeisse and Minshall 2017; Pereira et al. 2019; Rinaldi et al. 2021a, b
4	Development of a strategy for collaboration and innovation	Oyekan et al. 2017; Fan and Stevenson 2018; Bag et al. 2021c; Huang et al. 2021a, b
5	Effective additive manufacturing processes	Gardan 2016; Oettmeier and Hofmann 2016; Achillas et al. 2017; Ghobadian et al. 2020
6	Supply chain risk management	Tuck et al. 2007; Ho et al. 2015; Durach et al. 2017; Fan and Stevenson 2018;
7	Effective inventory management	Berman 2012; Holmström et al. 2016; Cestana et al. 2019; Hedenstierna et al. 2019
8	Proactive top management	Singh et al. 2007; Dwivedi et al. 2017;. Devi et al. 2020; Ivanov and Das 2020; Sonar et al. 2020; Bag et al. 2021d
9	Efficient information sharing process	Sanders et al. 2016; Zhong et al. 2017; Routroy et al. 2018; Dubey et al. 2019; Baah et al. 2021; El Baz and Ruel 2021
10	Distributed manufacturing system	Bogue 2013; Bogers et al. 2016; Pour et al. 2016; Pereira et al. 2019; Fonseca and Azevedo 2020; Luomaranta and Martinsuo 2020; Shokrani et al. 2020; Chowdhury et al. 2021
11	Resource allocation for digitalization	Gupta and George 2016; Devi et al. 2020; Sharma et al. 2020; Bag et al. 2021c; Raji et al. 2021
12	Antifragile supply chain	Derbyshire and Wright 2014; Chowdhury and Quaddus 2016; Delic et al. 2019; Nikookar et al. 2021
13	Rapid market responsiveness	Rogers et al. 2016; Chekurov et al. 2018; Jimo et al. 2019; Devi et al. 2020
14	Integrated manufacturing processes	Jin et al. 2013; Gebler et al. 2014; Valilai and Houshmand 2015; Delic et al. 2019; Dircksen and Feldmann 2020
15	Effective knowledge management process	Shah et al. 2017; Deaton and Deaton 2020; Ivanov and Rozhkov 2020; Equbal et al. 2021; Ivanov and Dolgui 2021; Sarkis 2021
16	Design freedom and Customisability	Attaran 2017; Ghaffar et al. 2018; Ivanov and Das 2020; Engelseth et al. 2021

Table 5 Structural Self-Interaction Matrix (SSIM)

Factors		16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
1	**DSTA**	O	V	V	V	V	X	V	V	A	V	V	V	A	V	V	-
2	**CDM**	A	A	A	V	V	A	A	A	A	X	O	A	A	A	-	-
3	**RMLT**	X	O	A	V	V	A	A	A	A	V	A	A	A	-	-	-
4	**DSCI**	V	V	V	V	V	V	V	V	A	V	V	V	-	-	-	-
5	**EAMP**	V	A	A	V	V	A	V	A	A	V	A	-	-	-	-	-
6	**SCRM**	V	A	X	V	V	A	V	A	A	V	-	-	-	-	-	-
7	**EIM**	A	A	A	V	V	A	A	A	A	-	-	-	-	-	-	-
8	**PTM**	O	V	V	V	V	V	V	V	-	-	-	-	-	-	-	-
9	**EISP**	V	V	V	V	V	A	V	-	-	-	-	-	-	-	-	-
10	**DMS**	V	A	O	V	V	A	-	-	-	-	-	-	-	-	-	-
11	**RAD**	O	V	V	V	V	-	-	-	-	-	-	-	-	-	-	-
12	**AFSC**	A	A	A	A	-	-	-	-	-	-	-	-	-	-	-	-
13	**RMR**	A	A	A	-	-	-	-	-	-	-	-	-	-	-	-	-
14	**IMP**	O	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	**EKMP**	V	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	**DFC**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

top-level factors in the hierarchy. The top-level factor of the hierarchy would not help achieve any other factor above it. Once the top-level factor is identified, it is separated from the other factors. The process is then repeated to find the next level. This process is continued until the level of all the factors is determined. In Table 8, we can see that there are a total of 12 levels across which these 16 factors will be arranged.

4.4 Formation of TISM model

A structural model, which we also call a digraph is developed based on the final reachability matrix. In the model, critical success factors are arranged and represented by nodes, and the relationship linkages between two factors as obtained in the final reachability matrix are also depicted. The level of each factor achieved during level partitioning helps in assigning the levels for each element. The final TISM model formed from the levels of each factor is shown in Fig. 3

4.5 Matrice d'Impacts Croisés Multiplication Appliqués à un Classement (MICMAC) analysis

Once the TISM model is developed, MICMAC analysis is performed to place the factors into one of the four quadrants. MICMAC analysis was first used by Duperrin and Godet in 1973. It is based on a system of multiplication of

Table 6 Initial reachability matrix

Factors		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	**DSTA**	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	0
2	**CDM**	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0
3	**RMLT**	0	1	1	0	0	0	1	0	0	0	0	1	1	0	0	1
4	**DSCI**	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
5	**EAMP**	0	1	1	0	1	0	1	0	0	1	0	1	1	0	0	1
6	**SCRM**	0	0	1	0	1	1	1	0	0	1	0	1	1	1	0	1
7	**EIM**	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0
8	**PTM**	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
9	**EISP**	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1
10	**DMS**	0	1	1	0	0	0	1	0	0	1	0	1	1	0	0	1
11	**RAD**	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	0
12	**AFSC**	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
13	**RMR**	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
14	**IMP**	0	1	1	0	1	1	1	0	0	0	0	1	1	1	0	0
15	**EKMP**	0	1	0	0	1	1	1	0	0	1	0	1	1	1	1	1
16	**DFC**	0	1	1	0	0	0	1	0	0	0	0	1	1	0	0	1

Table 7 Final reachability matrix

Factors		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Driver power
1	**DSTA**	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1*	14
2	**CDM**	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0	4
3	**RMLT**	0	1	1	0	0	0	1	0	0	0	0	1	1	0	0	1	6
4	**DSCI**	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	15
5	**EAMP**	0	1	1	0	1	0	1	0	0	1	0	1	1	0	0	1	8
6	**SCRM**	0	1*	1	0	1	1	1	0	0	1	0	1	1	1	0	1	10
7	**EIM**	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0	4
8	**PTM**	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1*	16
9	**EISP**	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	12
10	**DMS**	0	1	1	0	0	0	1	0	0	1	0	1	1	0	0	1	7
11	**RAD**	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1*	14
12	**AFSC**	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
13	**RMR**	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2
14	**IMP**	0	1	1	0	1	1	1	0	0	1*	0	1	1	1	0	1*	10
15	**EKMP**	0	1	1*	0	1	1	1	0	0	1	0	1	1	1	1	1	11
16	**DFC**	0	1	1	0	0	0	1	0	0	0	0	1	1	0	0	1	6
Dependency		4	14	12	2	9	8	14	1	5	10	4	16	15	8	6	12	140

Numbers marked with * represent transitivity

matrices (Govindan et al. 2012). MICMAC aims to group the factors based on their dependence and driving powers. It helps in understanding whether the factor drives the other factors or is dependent on other factors. A direct relationship matrix reveals the variables with maximum direct impact but fails to identify the hidden variables which at times might have high influence. MICMAC analysis helps in understanding the diffusion of these impacts (Saxena et al. 1990). The necessary information can be derived from the final reachability matrix, where the row total gives the driving power, and the column total gives the dependence for each factor. A graph is then plotted with X-axis representing the dependence power and Y-axis representing the driving power. The four quadrants of the graph are as mentioned below:

- Autonomous: Factors with low dependency and low driving power are placed in the first quadrant.
- Dependent: Factors with high dependency and low driving power are placed in the second quadrant.
- Linkage: Factors with high dependency and high driving power are placed in the third quadrant.

Table 8 Level partitions for barriers based on multiple iterations

Factor	Reachability set	Antecedent set	Intersection set	Level
1	1,2,3,5,6,7,9,10,11,12,13,14,15,16	1,4,8,11	1,11	10
2	2,7,12,13	1,2,3,4,5,6,7,8,9,10,11,14,15,16	2,7	3
3	2,3,7,12,13,16	1,3,4,5,6,8,9,10,11,14,15,16	3,16	4
4	1,2,3,4,5,6,7,9,10,11,12,13,14,15,16	4,8	4	11
5	2,3,5,7,10,12,13,16	1,4,5,6,8,9,11,14,15	5	6
6	2,3,5,6,7,10,12,13,14,16	1,4,6,8,9,11,14,15	6,14	7
7	2,7,12,13	1,2,3,4,5,6,7,8,9,10,11,14,15,16	2,7	3
8	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16	8	8	12
9	2,3,5,6,7,9,10,12,13,14,15,16	1,4,8,9,11	9	9
10	2,3,7,10,12,13,16	1,4,5,6,8,9,10,11,14,15	10	5
11	1,2,3,5,6,7,9,10,11,12,13,14,15,16	1,4,8,11	1,11	10
12	12	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16	12	1
13	12,13	1,2,3,4,5,6,7,8,9,10,11,13,14,15,16	13	2
14	2,3,5,6,7,10,12,13,14,16	1,4,6,8,9,11,14,15	6,14	7
15	2,3,5,6,7,10,12,13,14,15,16	1,4,8,9,11,15	15	8
16	2,3,7,12,13,16	1,3,4,5,6,8,9,10,11,14,15,16	3,16	4

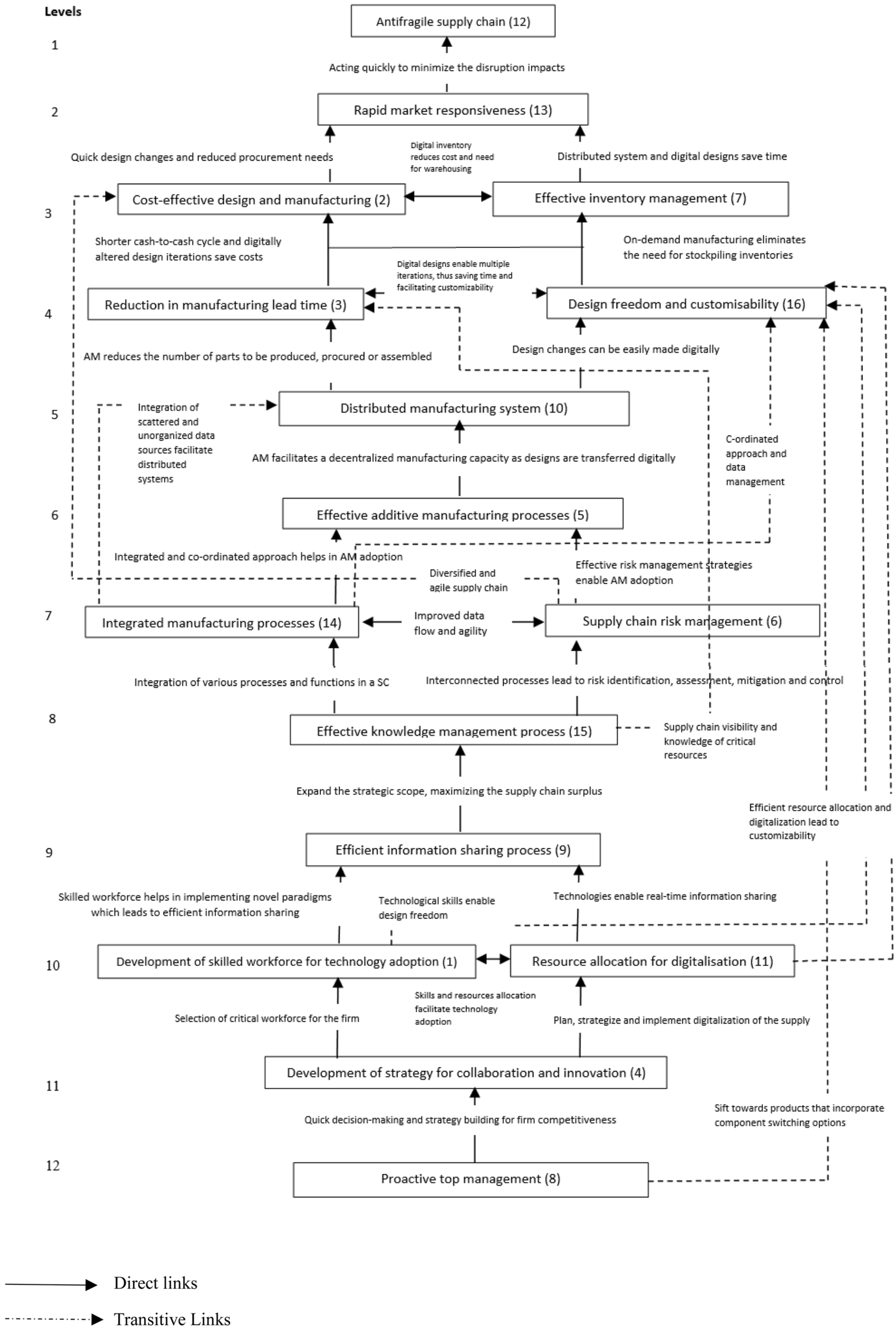

Fig. 3 TISM-based model

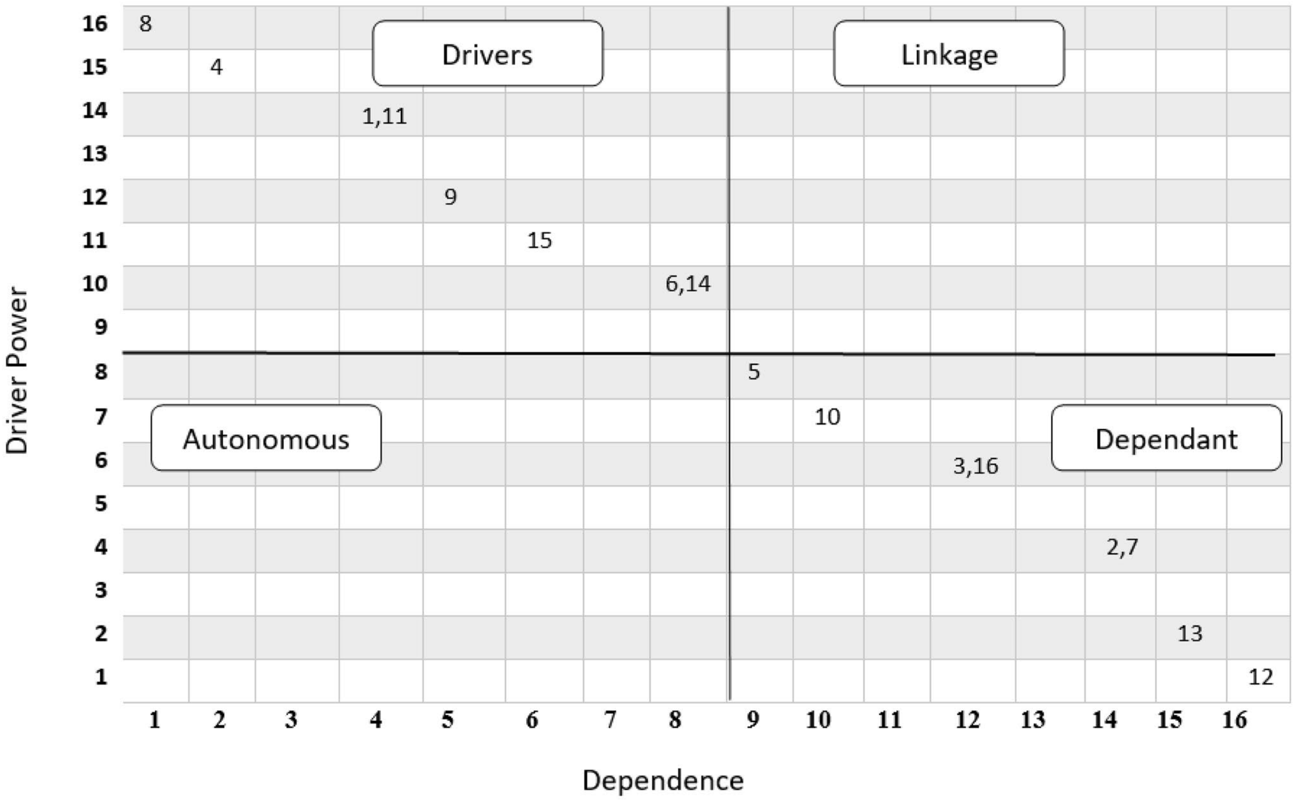

Fig. 4 Driving power and dependence diagram

- Driver: Factors with weak dependence and high drive power are placed in the fourth quadrant.

These quadrants have been shown in Fig. 4 along with the factors belonging to each quadrant.

5 Discussion

The Covid-19 driven disruption has made resilience a buzzword for business firms. A resilient firm can be considered an adaptive system that withstands disruption and recovers from it in quick time. In contrast, an antifragile supply chain does not adapt but evolves. AM has gained huge attention in recent times as a technological intervention to save the supply chain from disruption. We see many applications of AM across various sectors such as aerospace, automotive components, medical supplies, jewelry, and pharmaceuticals. This study reveals its importance in building an antifragile supply chain.

The first objective of the study was to identify the factors affecting the implementation of additive manufacturing technologies to build an antifragile supply chain during disruption. To begin with, nineteen critical success factors to build an antifragile supply chain were identified through literature. Seven experts were identified across various fields who substantiated the findings through the Delphi method and that resulted in a total of sixteen factors to work with. The second objective was to develop a structural relationship framework for the factors identified. For this purpose, the experts were contacted again to collect their response through the Delphi method, and accordingly, the reachability matrix was developed. This led to the development of a TISM based model which clearly explains the interrelations between these factors. The TISM model reveals the importance of having proactive top management whose quick decision-making and strategic planning skills will help in developing strategies for collaboration and innovation across the supply chain, which is an important factor, especially during a disruption. This would provide firms with access to new knowledge and help them learn and innovate for enhanced performance. These strategies will also help the firm in the selection of critical workforce who are skilled and assist the firm in technology adoption. The skilled workforce helps in implementing novel paradigms which leads in efficient information sharing. The firms also build strategies to plan for resource allocation and implementation of digitalization of the supply chain. These technologies enable real-time information sharing in the supply chain. The efficient information sharing process leads to an effective knowledge management process by facilitating the firms in expanding their strategic scope and maximizing the supply chain surplus. This knowledge management helps in the integration of various processes and functions in a supply chain and these interconnected processes lead to risk identification, assessment, mitigation, and control. Integrated and coordinated approaches and effective risk management strategies help the firm in AM adoption and its effective implementation. As the designs can be digitally stored and transferred, AM facilitates a decentralized manufacturing system. This moves the manufacturing closer to the customer and digital designs allow multiple iterations of the product before printing as the changes are made to the 3D design digitally. This provides design freedom and customisability. Also, since AM reduces the number of parts required to be produced, procured, or assembled, the manufacturing lead time is reduced. This helps the firms to design and manufacture new products cost-effectively. Since the stock can be digitally held, it reduces the need to have a huge inventory. These quick design changes, reduced procurement needs, distributed systems, and digital designs save a lot of time and help the firms in rapid market responsiveness. During a disruption, these help the firms in acting quickly and minimizing the effects of disruption which ultimately leads to building an antifragile supply chain.

The third objective was to categorize and analyze these factors based on driving and dependence power. The MICMAC analysis helps in classifying the factors into the following clusters:

- Autonomous factors: These factors have weak driving and dependence power indicating that they are disconnected from the system and do not have much influence on developing the antifragile supply chain. In this study, there are no factors categorized as autonomous meaning that all 16 factors identified are important for the system.
- Dependent factors: These factors have high dependence and low driving power. These factors are important for an organization and can be seen at the top of the TISM model. They represent the desired objectives for an organization. In this study, effective additive manufacturing processes, distributed manufacturing system, effective knowledge management process, reduction in manufacturing lead time, design freedom and customisability, cost-effective design and manufacturing, effective inventory management, rapid market responsiveness, and antifragile supply chain are the dependent factors. The success of these factors is strongly dependent on other factors.
- Linkage factors: The results reveal that there are no linkage factors that have strong driving power as well as strong dependence. These variables are unsteady and any action on these variables will influence other variables as well as the feedback on them. Thus, it can be inferred that among all the 16 factors chosen for this study, no factor is unstable, and the factors do not require handling with care while dealing with them.
- Driver factors: These factors help organizations in achieving their desired objectives and are classified as independent factors or drivers. They have high driving power and low dependence and are investigated from a strategic perspective by the top management. In this study, supply chain risk management, integrated manufacturing processes, efficient information sharing process, development of a skilled workforce for technology adoption, resource allocation for digitalization, development of a strategy for collaboration and innovation, and proactive top management are the drivers.

Antifragile supply chain, which is at the top of the hierarchy in the TISM model revealing its low driver power and high dependence. Thus, it has a more competitive orientation. Proactive top management, on the other hand, is at the bottom of the hierarchy revealing its low dependence and high driver power. Thus, it has a more strategic orientation. Hence, a competitive advantage can be achieved by continuously enhancing the capabilities of the drivers. Also, the study has no autonomous and linkage factors. All the factors are either drivers or dependants stating that all are steady factors and important for the model. They either drive the other factors or are dependent on other factors for their success.

5.1 Theoretical contributions

This study makes substantial contributions to the literature. The literature review revealed that most of the studies focus on building a resilient and/or robust supply chain. These studies discuss how to make the supply chain bounce back quickly in the event of a disruption or an exogenous shock such as the Covid-19 pandemic. However, only a handful of studies could be identified which talk about building an antifragile supply chain that thrives in uncertainty and chaos. This indicates that the focus of researchers is towards tackling the disruptions and saving the supply chain from any adversaries. On the contrary, the shift from robustness and resilience to antifragility requires the firms to deliberately cause some level of disruption to the supply chain, so that it embraces disruption and gains from it rather than avoiding it altogether. The few studies that have discussed antifragility focus on the need for antifragility and how it impacts the supply chain. None of the studies in the literature have focused on the factors that lead to antifragility. In this regard, this study adopts a very novel approach in determining the factors that could lead to an antifragile supply chain and how additive manufacturing capabilities can be utilized to lead to antifragility. The study draws the attention of the researchers towards a concept less explored. The conceptual framework is built using the TISM approach and discusses a firm's strategies and decisions in a turbulent environment. The study figures out the relevant factors towards an antifragile supply chain, determines the hierarchies and interlinks and classifies them based on driving and dependence power.

5.2 Implications to practice

The recent worldwide disruption to operations and supply chains has got the firms rethinking their strategies. The need of the hour is to develop dynamic capabilities which would prove beneficial in these uncertain times so that the firms can combat and learn from disruption to avoid any negative consequences on the firms' overall performance. Currently, resilience and robustness are the go-to strategies for a firm to save itself in the face of adversities. This study brings to the forefront, the concept of antifragility which points out the need to embrace disruption and learn from them. The study helps the firms develop a mind shift towards building a supply chain that sees disorder as an opportunity to learn and grow. Finally, the nexus between antifragility and digitalization develops a fertile ground for the adoption of additive manufacturing technologies. This study reveals how AM can be used as a competitive advantage by the firms to combat any negative consequences on its overall performance in the face of disruption. The structural framework, its hierarchies, and interlinks can be utilized by decision-makers as a powerful tool to understand the cause and effect. Also, the MICMAC analysis helps the firms understand what factors are driving the changes and which are dependent on others. Efforts of the decision-makers can now be directed towards achieving an antifragile supply chain by understanding the links and prioritizing their actions towards the goal. These actions will help the firms prepare better in case of future disruptions to their supply chains.

6 Conclusion, limitations, and future scope

In the post-Covid-19 era, supply chain resilience has gained the attention of researchers and practitioners. Supply chain resilience is the ability of a supply chain to return to its pre-disrupted mode in an acceptable period. An antifragile supply chain strives to embrace the disorder and gain from it rather than avoid it. Here, we can find its analogy with any vaccination, the aim of which is to intentionally expose our immune system to the virus to build a stronger immunity towards it. Similarly, an antifragile supply chain helps firms to convert the challenges into opportunities. During the recent outbreak, additive manufacturing evolved to become a ubiquitous technology and the world saw its potential applications in the printing of medical supplies. Quite a few studies have discussed how additive manufacturing technology can be utilized to combat the Covid-19 challenges. Several industries and business sectors, such as the medical sector, used AM to manufacture customized and cost-efficient products in a timely fashion. Recent improvements in AM technology enable co-designing and mass-personalization. Operational and technological innovations have also been done to push the boundaries of customization and provide high volume at a low cost. AM helps the firms in overcoming the traditional manufacturing constraints, including but not limited to inventory buffers and tooling requirements. AM's potential to rapidly produce unlimited range of products can prove to be a winning factor during a disruption for any firm.

Existing literature talks about resilient and robust supply chains but factors leading to an antifragile supply chain have not yet been discussed. In this study, through literature review, initially, nineteen factors are identified for an antifragile supply chain. Delphi method is used to collect experts' opinions to corroborate the findings which led to the final sixteen factors for this study. Using TISM-MICMAC, the hierarchy and interaction of these factors are analyzed and the factors are then clubbed as drivers and dependants. The results reveal the importance of proactive top management to implement AM, which ultimately leads to an antifragile supply chain. The TISM-MICMAC approach used in this study provides a macro picture of the critical factors to build an antifragile supply chain. Findings will help managers in decision-making to prepare for future disruptions in the supply chain. However, this study has some limitations. It gives only the interrelationships between the factors and fails to assign relative importance to the factors. Hence, for further validation of findings, Structural Equation Modeling (SEM) and m-TISM could be applied as future scope of the study.

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Declarations

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