



Assessing supply chain resilience to the outbreak of COVID-19 in Indian manufacturing firms

Gaurav Kumar Badhotiya¹ · Gunjan Soni² · Vipul Jain³ · Rohit Joshi⁴ · Sameer Mittal^{5,6}

Received: 16 April 2021 / Revised: 29 October 2021 / Accepted: 16 November 2021
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Abstract

As the world has seen the impact of COVID-19, development of resilient supply chain strategies has emerged as top priority. The inconsistent demands, product consumption and the shorter lifecycle of products during the pandemic needs appropriate planning and designing to make the supply chain more resilient. In this study, an analytical model is proposed to assess the resilience of supply chain to overcome the effect of the disruption impacts. The supply chain risks will depend on the nature of the business and therefore, besides literature review on supply chain resilience the inputs from experts were required. The interdependency among the indicators was analysed by employing Interpretive Structural Modelling (ISM) and demonstrated with the help of a framework. The strength of the interdependence is assessed using Bayesian Network approach. BN transformed the qualitative expert inputs to quantitative assessment by utilising the principles of conditional probability. Three cases from Indian manufacturing industries were used to demonstrate and assess the critical supply chain resilience indicators using integrated ISM-BN approach. The cases showed that the proposed approach can assist decision makers in identifying the critical indicators to be focused towards improving the supply chain resilience to overcome the outbreak of Covid-19 pandemic. A comparative analysis of the supply chain risk indicators has also been performed, thereby extending the practical implication of supply chain resilience.

Keywords Supply chain resilience · Disruption impacts · Covid-19 · Interpretive structural modelling · Bayesian network

✉ Gunjan Soni
gsoni.mech@mnit.ac.in

Gaurav Kumar Badhotiya
gkb.choudhary@gmail.com

Vipul Jain
vipul.jain@vuw.ac.nz

Rohit Joshi
rj@iimshillong.ac.in

Sameer Mittal
sameer.mittal@jklu.edu.in

- ¹ Mechanical Engineering Department, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India
- ² Mechanical Engineering Department, Malaviya National Institute of Technology, Jaipur, Rajasthan, India
- ³ School of Management, Victoria University of Wellington, Wellington, New Zealand
- ⁴ Indian Institute of Management, Shillong, Meghalaya, India
- ⁵ Institute of Management, JK Lakshmipath University, Jaipur, India
- ⁶ Unit of Information and Knowledge Management, Tampere University, Tampere, Finland

1 Introduction

Disruption is an inherent part of global context of all supply chains resulting in unexpected consequences (Golan et al. 2020). Losing competitiveness and the reduction in the short-term financial performance are some of the effects of the supply chain disruption (Ji and Zhu 2008; Karwasra et al. 2021). The supply chain risks and disruptions can adversely affect an organization's growth and success (Belhadi et al. 2021), so supply chains must be made resilient to overcome risks and disruptions and work effectively. Supply chain Resilience (SCR) is the ability of a supply chain to anticipate the risk, reduce its impact and rapidly come back to the optimized state through survival, evolution, adaptability and growth (Ponomarov and Holcomb 2009). SCR focuses on developing the capability of a system to prepare for unforeseen disruptive events and recover the supply chain to its original state (Jain et al. 2017). The resilience is also defined as the response to an unpredicted interruption such as a terrorist attack, and getting back to its usual operations. Similarly, SCR has been

considered as the adaptive capability of a system, to gain advantages from the disruptions (Hohenstein et al. 2015). Therefore, in total, SCR offers a way to provide protection strategies from the risks and the disruptions present in the supply chains.

The recent COVID-19 pandemic has affected the global supply chain enormously. The epidemic outbreak is a special case of supply chain risk having low frequency, high uncertainty, and long duration of effect (Ivanov 2020a). The supply and demand was imbalanced due to the outbreak of Covid-19 at both global and local level (Kumar et al. 2021). The Covid-19 outbreak has been a constraint to the supply chain resilience of the company due to shortage of supply, production stops and imbalanced supply demand situation (Ivanov and Dolgui 2020). Therefore there is a need to assess the resilience of supply chain to cope up with the disruption impacts of Covid-19 outbreak.

The objectives of this study are (i) to identify and discuss about SCR indicators, (ii) to model the interdependency among the indicators, (iii) to assess the resilience of three case companies supply chain during the outbreak of Covid-19 by employing the critical indicators and iv) perform a comparative analysis of result. To answer these questions, a systematic literature review is performed, and sixteen indicators for supply chain resilience are identified. Later, an integrated Interpretive Structural Modelling and Bayesian Network methodology is proposed. The ISM methodology is used to identify the interdependencies, whereas, the BN is constructed to assess the SCR which eventually enhance the supply chain performance. Based on the outcome of the assessment of SCR, suggestions to overcome with the situation are provided.

The research presented in this study contributes to both the literature on impact of Covid-19 disruption and measuring supply chain resilience. We have identified a comprehensive list of SCR indicators and also analyse the interdependency among the factors. We also demonstrated the application of the study by implementing the integrated ISM-BN approach to measure SCR of three Indian manufacturing industries. This study will assist the supply chain managers in examining and improving their supply chain performance and make it resilient against disruptions such as current Covid-19 pandemic.

This paper is structured as follows: the current section introduces the research problem, objectives, and contributions. Section 2 presents literature review of articles on assessment of SCR along with articles that have considered the Covid-19 situation. Section 3 provides the research methodology followed in this paper. Section 4 presents the identification and definition of the supply chain resilience indicators. Section 5 discusses the results pertaining to the assessment of SCR considering the case companies. Section 6 discusses the results and implication of the research

work. Finally, Sect. 7 ends with conclusion, limitations and future research directions.

2 Literature review

This section presents review of relevant literature on assessment of SCR and Covid-19 pandemic and SCR.

2.1 Supply chain resilience assessment

Supply chain resilience focuses on preparing the plan and constructing the supply chain network that can foresee the adverse events and adapt to the interruptions while keeping the supply chain unaffected. Existing research have focused on creating framework for SCR (Ehrenhuber et al. 2015; Ali et al. 2017), investigating influence of supply chain capabilities on achieving SCR (Mandal 2013), validating measurement dimensions of SCR (Chowdhury and Quaddus 2016). Razmi et al. (2017) identified and constructed causal relationship among the SCR factors. (Jain et al. 2017) presented a hierarchy based model for SCR and validated empirically. Few studies have also worked on the assessment of SCR through case studies (Hosseini et al. 2016; Yazdanparast et al. 2021). A systematic framework for assessment and strategies to foster SCR is proposed by Shashi et al. (2020).

Few articles in the literature have worked upon the assessment of resilience of supply chain as classified in Table 1. (Spiegler et al. 2012) discussed ways of measuring resilience and applied a control engineering approach for assessment of SCR. Pettit et al. (2013) proposed a measurement tool named as Supply chain resilience assessment and management based on the framework of Pettit et al. (2010). A qualitative methodology is followed and data was gathered from manufacturing and service firms to validate the proposed framework for improving resilience. Soni et al. (2014) have analysed and proposed an index for measurement of SCR. A total of ten enablers were identified and a model was proposed using graph theory and interrelationship analysis was performed using ISM approach. Hosseini et al. (2016) have proposed a framework for measuring the assessment of system resilience using Bayesian network approach. The approach was implemented in an Iranian sulfuric acid manufacturing industry for quantifying the resilience. Pavlov et al. (2018) considered a multi stage supply chain for investigation of disruption at different locations in the chain. The network reliability was analysed by implementing hybrid fuzzy-probabilistic approach and genome method. Dixit et al. (2020) considered network structural parameter to assess SCR of 23 Indian firms. The worst case performance of supply chain network is assessed by conditional-value-at-risk concept. Recently, Yazdanparast et al. (2021) have identified 16 enablers of SCR and measured resilience of an

Table 1 Literature on assessment of supply chain resilience

S.no	Publication	Methodology	Solution approach	Type of industry	Outcome
1	Spiegler et al. (2012)	Quantitative	Control Engineering approach	NA	Analytical framework
2	Pettit et al. (2013)	Qualitative	Focus group and Case study method	Manufacturing and Service firms	Assessment tool
3	Soni et al. (2014)	Quantitative	Graph theory and ISM	NA	SCR index
4	Hosseini et al. (2016)	Quantitative	Bayesian networks	Manufacturing	Conceptual framework
5	Pavlov et al. (2018)	Quantitative	Hybrid fuzzy-probabilistic	NA	Supply chain design resilience index
6	Dixit et al. (2020)	Quantitative	Simulation approach	Indian firms	Analysed worst case performance
7	Yazdanparast et al. (2021)	Quantitative	Z-number data envelopment analysis and neural network	Automotive supply chain	Conceptual framework
8	Moosavi and Hosseini (2021)	Quantitative	Simulation approach	Manufacturing	Measurement of resilient strategies

Iranian automotive supply chain. Z-number data envelopment analysis and neural network approach was employed for efficiency score calculation.

2.2 Covid-19 pandemic and supply chain resilience

Research on investigation of the effect of epidemic outbreak on supply chain has emerged recently. A systematic literature review of resilience analytics in supply chain modelling in the context of Covid-19 pandemic is presented by Golan et al. (2020). El Baz and Ruel (2021) investigated the role of supply chain risk management (SCRM) in mitigation of the effect of Covid-19 outbreak on supply chain resilience and robustness. From the survey of 470 French firms, the study provides evidence of the role of SCRM in fostering SCR. Ivanov and Das (2020) conducted a simulation based study to examine the impact of pandemic on global supply chain. Three scenarios were considered where the epidemic originates, propagates to distribution centre, and to the customer. Ivanov (2020b) theorized a new notion named as viable supply chain which is able to maintain itself in changing environment. A model was presented integrating the concepts of agility, resilience and sustainability. Belhadi et al. (2021) investigated supply chain resilience to the covid-19 outbreak in manufacturing and service operations considering case of automobile and airline supply chain. The empirical survey of 145 firms and semi-structured interview were taken to understand the supply chain resilience strategies.

SCR has been investigated extensively in the literature, but the earlier studies are focusing on creating operational capabilities by collaborating with the supply chain partners. Although, research has been carried out from different perspectives of supply chain, however, substantial work has not been done when it comes to the performance measurement of the supply chains. It has also been identified that

the organizational supply chains will be more successful, if they can measure the performances of the supply chain (Jüttner and Maklan 2011). Additionally, such measures and measurements can examine the suitability of techniques, an absence of which can further complicate the understanding of the factors pertaining to the supply chain risks (Saleheen et al. 2018). A pandemic has unique implication for supply chain (Ivanov and Das 2020). The Covid-19 pandemic has also affected the resilience of global supply chain. Most firms and supply chains were unprepared for the disruption caused by Covid-19 pandemic. The lack of knowledge on dealing with the situation limits readiness and ability of supply chain to react (Ali et al. 2021). There is scarcity and need to analyse the impact of pandemic on supply chain resilience (Ivanov 2020b; Ivanov and Das 2020; Ivanov and Dolgui 2020). This study fills this gap by assessing the supply chain resilience of three Indian manufacturing companies during the outbreak of Covid-19 pandemic. To propose resilience strategies to the outbreak of Covid-19, this study also analyse the interrelationship of SCR indicators.

3 Research methodology

The methodology involved in the current research has been inspired by previous research (Wu et al. 2015). Figure 1 outline the complete research methodology employed in this paper. As can be seen from the figure, the methodology can be broadly divided into two phases: Identification of SCR indicators and analysis of interdependency between SCR indicators. The identification phase involves extraction of SCR indicators from the extant literature and discussion with academicians and industry experts to establish a list of prevailing SCR indicators. However, from the definitions of the indicators and from the opinion

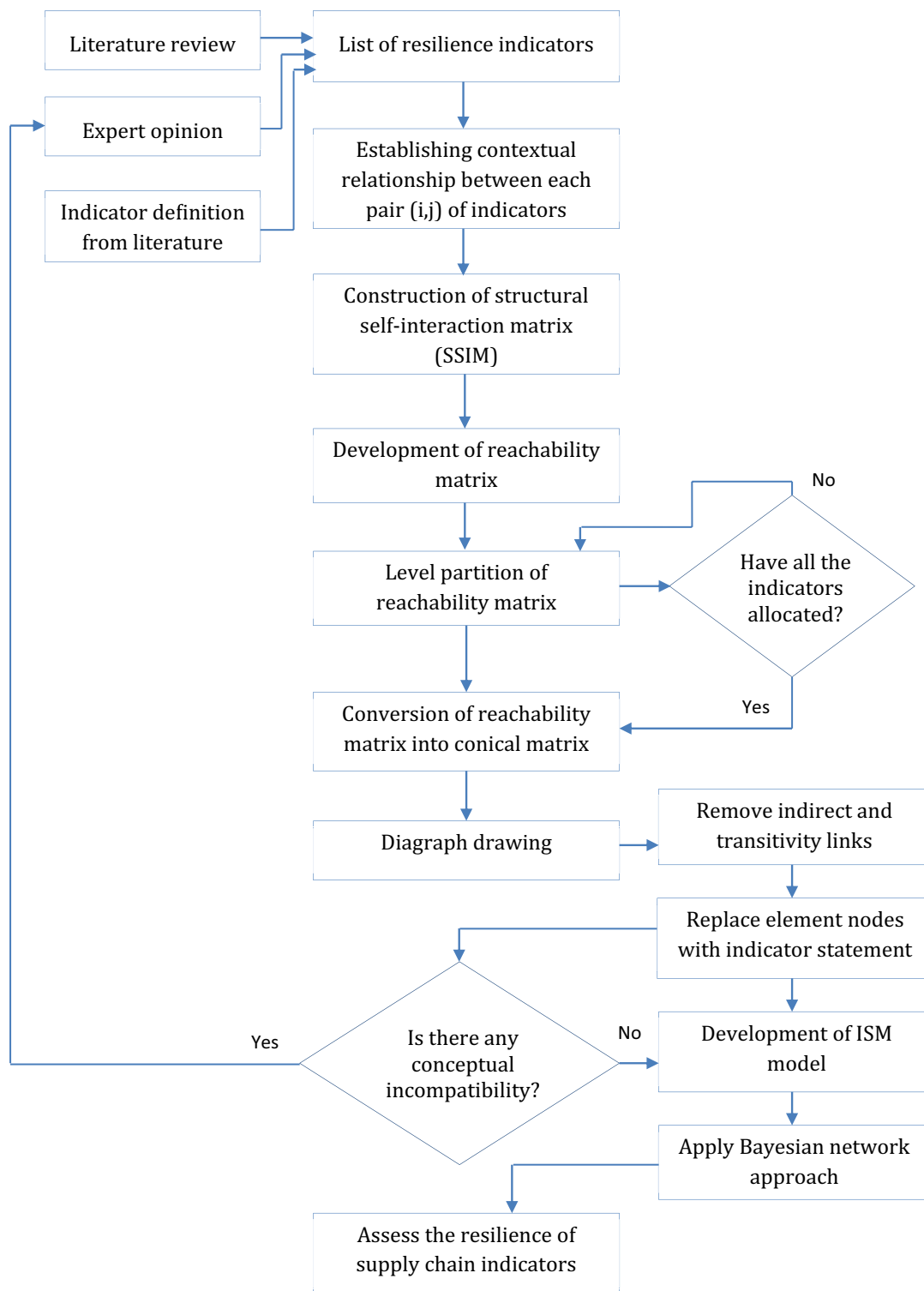


Fig. 1 Methodology framework employed in this study

of industry experts, it can be considered that they have interdependencies among each other. For example, it was identified that the active information sharing was influencing all the indicators. Similarly, it was identified that

agility is influenced by all the factors. These results were derived with the help of a survey questionnaire, which was shared via email with the experts from both academics and practice.

This study uses an integrated Interpretive Structural Modelling (ISM) and Bayesian Network (BN) approach for analysis of SCR indicators. The interdependency among the indicators is analysed by Interpretive Structural Modelling (ISM) methodology. There exists many methods that are used for prioritization and ranking of factors, but ISM is a widely used method for providing hierarchical structure (Yadav and Desai 2017; Chauhan et al. 2020; Liu et al. 2021). To model dependency in this complex network, in the next phase, Bayesian Network (BN) is implemented which uses probabilities to evaluate the critical indicators in the supply chain. As mentioned by Hosseini and Ivanov (2020), in their literature review that BNs are the appropriate tools for measuring SC resilience. The interdependency model of ISM method is used to form the structure of the BN.

To illustrate the practical implication of the study, assessment of three manufacturing industries located in India is considered. The companies were facing supply chain disruption due to the Covid-19 pandemic. The purpose of the study was discussed with the industry experts and was asked to provide the information related to the probabilities of the indicators. Because of the Covid-19 pandemic situation, discussion and data collection was done in online mode.

Section 3.1 discusses the ISM methodology and Sect. 3.2 discusses the Bayesian network methodology.

3.1 Interpretive structure modelling (ISM)

Interpretive structure modelling (ISM) is used to identify the inter-relationship among all indicators. This methodology is referred as interpretive because it converts expert opinion to useful information (Bolaños et al. 2005). ISM is referred as structural as it employs the obtained results to construct the structure. This structure reflects the relationship between complex variables in a visible manner. As suggested by previous research, following steps were performed to apply ISM to this research:

- Step I. Identification of factors or indicators. During this research, the scientific literature was reviewed and opinion from academic and industry experts were taken to identify the indicators of the supply chain resilience.
- Step II. A contextual relationship is established with the help of expert's knowledge for each pair of supply chain resilience indicators identified in the step I.
- Step III. A structural self-interaction matrix (SSIM) showing the pair-wise relationship among supply chain resilience indicators was developed.
- Step IV. SSIM results in a reachability matrix to check the transitivity of the matrix.
- Step V. Finally, the reachability matrix is partitioned into different levels.

3.1.1 Structural self-interaction matrix

For analysing the interdependencies among the indicators, a "lead to" contextual relationship is chosen, where one variable influence another variable helps in achieving. The existence of a relation between any two barriers (m and n) and the associated direction of the relation is questioned while acknowledging the "lead to" contextual relationship. The direction of relationship between the barriers is denoted by four symbols (V, A, X, O), representation of which are as follows:

- V: Indicator m leads to indicator n .
- A: Indicators n leads to indicator m .
- X: Indicators m and n both leads to each other
- O: Indicators m and n are unrelated.

3.1.2 Reachability matrix

A binary matrix is obtained by converting the SSIM, referred to as the initial reachability matrix, by substituting the four symbols by 1 and 0 according to each case. For the substitution, following rules were followed:

- Write 1 in the (m, n) entry and 0 in the (n, m) entry if the entry in the SSIM is V.
- Write 0 in the (m, n) entry and 1 in the (n, m) entry if the entry in the SSIM is A.
- Write 1 in the both (m, n) and (n, m) entries if the entry in the SSIM is X.
- Write 0 in the both (m, n) and (n, m) entries if the entry in the SSIM is O.

The final reachability matrix is developed by following the above rules and after incorporating the property of transitivity. Transitivity is an assumption in the ISM which explains that if an indicator A is related to indicator B and indicator B is related to indicator C then the indicator A will be necessarily related to the indicator C. The final reachability matrix also shows the driving power and the dependence of each indicator. The driving power of an indicator is the total number of indicators (including itself) which it may impact. Dependence is the total number of indicators (including itself) which it may be impacting (Chauhan et al. 2017).

3.1.3 Level partitioning

Auxiliary model is an outcome of the final reachability matrix. The outcomes of reachability matrixes can also be used to frame distinctive partitions (Barve et al. 2007). The partitions can then be further utilized to recognize different structure properties. In this regard, the first step is to acquire

the reachability set and the antecedent set. Reachability set consists of the indicator itself and the indicators that are being influenced, while antecedent set consists of the indicator itself and the different indicators that may prompt it (Hasan et al. 2007). From that point onward, crossing point both the sets are resolved and level apportioning is finished. The best level indicators are having same reachability, and the antecedent sets and are critical as they are not achieved by the other indicators. Subsequent to getting the convergence and distinguishing the best factor, it will be expelled in promote thought and in a similar way different obstructions level can be resolved. The above expressed technique will help in developing the diagraph and decide the different levels of the auxiliary model.

3.2 Bayesian network

Bayesian networks (BN) were introduced by Pearl (1988), to capture dependency among system components. BNs are probabilistic graphical models also named as the probabilistic networks, belief networks or causal networks (Jensen 2001), that uses conditional probabilistic and Bayes theorem to acknowledge the arbitrary indicators. A comprehensive literature review of Bayesian networks for supply chain risk, resilience and ripple effect analysis is conducted by Hosseini and Ivanov (2020).

A directed acyclic graph (DAG) was utilized to create BN graphical models. The DAG comprises of a set of nodes that represent the indicator, whereas a set of edges represent the causal relationship among the indicators. This causal reliance is probabilistic in nature and is represented with the help of a structure of the nodes (Castillo et al. 1997). Each node has a limited arrangement of fundamentally unrelated states and is associated with a conditional probability distribution (CPD) that gives the probability of each state for every combination of significant worth so fits parents. The joint probability distribution (JPD) of a BN over its set of variables $X_i \in X = \{X_1 \dots \dots X_n\}$ is given by the result of all the CPDs.

$$P(X) = \prod_{i=1}^n P(X_i | pa(X_i))$$

where $pa(X_i)$ represents the parent nodes of X_i in the DAG (Jensen and Nielsen 2007).

BN works on the principle of qualitative causal reasoning. The interpretation of quantitative model from a qualitative perspective is achieved from integration of BN into ISM. The BN employs the principle of conditional dependencies and leads to a factorized joint distribution of indicators. The approach registers distribution probabilities in a given arrangement of indicators by utilizing earlier data of different indicators. It also arranges the nodes and the directed

circular segments, where the nodes represent the indicators in the framework, whereas, the arcs represent the relationships and the impact of the indicators (Barton et al. 2008). Every node has its own probability of the event. The probability of a root node is determined with the help of other arcs and nodes surrounding the root node. The nodes which are not directed towards the other nodes are referred to as the parent nodes. A conditional probability table (CPT) and the probabilities of the parent nodes form the base for the calculation of a BN. The CPT consists of the data of the conditional probabilities (Liao et al. 2008).

Once the CPT has been made for each indicator, the calculation is performed to calculate the strength of the relationships (using normalization) among the indicators of SCR. As a result, the probability estimations of the final objective is non-zero and the joined estimation of each CPT is 1 (Nadkarni and Shenoy 2004). For instance, for any two indicators A and B, the conditional probability of A, given that B has already occurred, is represented as P(A/B). Here, B is directed towards A. During the present study, CPTs were developed with the help of a discussion with the experts.

During this research, at first, a network is created with help of results derived from ISM hierarchy model, and subsequently, the relationships among all the indicators are created. This resultant model is used as a BN and then the conditional probability table is filled with the help of the experts.

4 Supply chain resilience indicators

SCR indicators also act at different phases of the supply chain, i.e. the anticipation phase, response & recovery, and resistance phase (Adobor and McMullen 2018; Singh et al. 2019). Table 2 identifies these indicators and categorized those under three phases.

4.1 Anticipation phase

Anticipation is the ability to determine potential future events or conditions (Pettit et al. 2010). It is a pre-disruption phase in the supply chain which prevents supply chains against disruption through minimizing the risk of occurrence (Shashi et al. 2020). In order to thrive in this competitive global market, Supply chain managers should be able to foresee future events for reducing the susceptibility of disruptions.

i. Supply chain visibility

Visibility describes the indispensability for transparency of processes and structures to quickly identify disruptions and to be able to implement changes in an

Table 2 Phase wise classification of SCR indicators

Phase	Indicator	Reference
Anticipation	Supply chain visibility	(Christopher and Peck 2004; Francis 2008; Pettit et al. 2010; Jüttner and Maklan 2011; Mandal 2013; Azadeh et al. 2014; Scholten et al. 2014; Ehrenhuber et al. 2015; Ali et al. 2017; Adobor and McMullen 2018)
	Situation awareness	(Pettit et al. 2010; Jain et al. 2017)
	Security	(Rice and Caniato 2003; Sheffi 2007; Pettit et al. 2010; Fiksel et al. 2015; Ali et al. 2017; Cui 2018)
	Sustainability	(Ponomarov and Holcomb 2009; Tukamuhabwa et al. 2015; Ali et al. 2017; Jain et al. 2017; Razmi et al. 2017)
	Supply chain risk management culture	(Christopher and Peck 2004; Scholten et al. 2014; Soni et al. 2014; Hohenstein et al. 2015; Chowdhury and Quaddus 2016; Jain et al. 2017; Shashi et al. 2020)
Response & recovery	Agility	(Christopher 2000; Lee 2004; Christopher and Peck 2004; Azadeh et al. 2014; Scholten et al. 2014; Soni et al. 2014; Hohenstein et al. 2015; Purvis et al. 2016; Ali et al. 2017; Jain et al. 2017; Razmi et al. 2017; Cui 2018; Adobor and McMullen 2018; Shashi et al. 2020)
	Supply chain velocity	(Jüttner and Maklan 2011; Azadeh et al. 2014; Scholten et al. 2014; Ali et al. 2017; Mandal 2017; Adobor and McMullen 2018)
	Market position/ sensitiveness	(Pettit et al. 2010; Fiksel et al. 2015; Ali et al. 2017; Jain et al. 2017)
	Knowledge management and information sharing	(Christopher and Peck 2004; Pettit et al. 2013; Scholten et al. 2014; Ali et al. 2017; Jain et al. 2017)
	Public-private partnership	(Jüttner and Maklan 2011; Scholten et al. 2014; Fiksel et al. 2015; Li et al. 2017)
Resistance	Flexibility	(Rice and Caniato 2003; Sheffi 2007; Ponomarov and Holcomb 2009; Pettit et al. 2010; Jüttner and Maklan 2011; Spiegler et al. 2012; Mandal 2013; Scholten et al. 2015; Fiksel et al. 2015; Hohenstein et al. 2015; Purvis et al. 2016; Chowdhury and Quaddus 2016; Ali et al. 2017; Cui 2018; Ivanov 2018; Adobor and McMullen 2018)
	Collaboration/ Integration	(Lee 2004; Christopher and Peck 2004; Sheffi 2007; Pettit et al. 2010; Jüttner and Maklan 2011; Spiegler et al. 2012; Mandal 2013; Scholten et al. 2014; Soni et al. 2014; Scholten and Schilder 2015; Fiksel et al. 2015; Hohenstein et al. 2015; Chowdhury and Quaddus 2016; Ali et al. 2017; Jain et al. 2017; Cui 2018; Adobor and McMullen 2018; Shashi et al. 2020)
	Redundancy	(Christopher 2000; Rice and Caniato 2003; Sheffi 2007; Azadeh et al. 2014; Scholten et al. 2014; Hohenstein et al. 2015; Chowdhury and Quaddus 2016; Purvis et al. 2016; Ali et al. 2017; Ivanov 2018; Adobor and McMullen 2018)
	Supply chain network design/ structure/ orientation	(Choi and Hong 2002; Pereira et al. 2014; Tukamuhabwa et al. 2015; Chowdhury and Quaddus 2016; Ali et al. 2017; Jain et al. 2017; Razmi et al. 2017; Shashi et al. 2020)
	Risk and Revenue Sharing	(Soni et al. 2014; Ali et al. 2017; Jain et al. 2017)
	Robustness	(Scholten et al. 2014; Purvis et al. 2016; Ivanov 2018; Shashi et al. 2020)

effective manner (Ehrenhuber et al. 2015; Adobor and McMullen 2018). According to Pettit et al. (2010), “*visibility is the knowledge of the status of operating assets and the environment*”. Francis (2008) defined supply chain visibility as the “*identity, location and status of entities transiting the supply chain, captured in timely*

messages about events, along with the planned and actual dates/times for these events”. It provides visuals about upstream and downstream inventory, details about various activities and processes, demand and supply, logistics and transportation through cooperation and information sharing across the supply chain.

ii. **Situation awareness**

Sensing is the skill of managing good forecasts and realizing processes ahead of time. Situation awareness is a comprehensive understanding of the supply chain vulnerabilities and planning for the required actions. Awareness requires the ability to anticipate the risks with the help of the early cautioning systems (Jain et al. 2017).

iii. **Security**

Security is a crucial component of supply chain resilience that provides defence against deliberate disruption, intrusion or attack such as terrorism, cyber-attack (Pettit et al. 2010; Tukamuhabwa et al. 2015). To counter the disruptions, security needs to be thought ahead of the planning phase of the supply chain (Rice and Caniato 2003).

iv. **Sustainability**

Sustainability focuses on meeting the needs of present using resources without compromising the ability of future generations to meet their own needs (Sws WCED 1987). Sustainability compliance with social, economic and environmental requirements and thus plays a key role in mitigate SC risks (Tukamuhabwa et al. 2015).

v. **Supply chain risk management culture**

A risk management culture is highly desirable in an organization to understand the concept and achieve resilience. Organizations should have a supply chain expert who can anticipate the supply chain risks that can adversely affect the organization (Choi and Hong 2002). This culture helps to identify and mitigate the supply chain risk and its likelihood (Chowdhury and Quaddus 2016).

4.2 Response & recovery phase

Supply chains should be able to respond to the subtle changes and recover themselves (Pettit et al. 2010). Recovery from disruption is a reactive capability of supply chain to restore back to the original state.

i. **Agility**

Agility can be defined as the ability of a system to grow in an unpredictable and continuously changing business environment (Christopher 2000; Razmi et al. 2017)). The organization is at higher risk where response time to changes is too much (Raut et al. 2021). According to Christopher and Peck (2004), “*Supply chain agility can be defined as the ability to respond quickly to unpredictable changes in demand or supply*”. Agility is strategic capability of the system to respond quickly to the external changes (Tarigan et al. 2021).

ii. **Supply chain Velocity**

Supply chain velocity is defined as the rate by which the chain recovers from the disturbance (Azadeh et al. 2014). It is the ability to complete an activity as quickly as possible (Carvalho et al. 2012). The concern is on increasing the time to respond to market changes which depends on the effective information sharing among members of the supply chain (Ali et al. 2017).

iii. **Market position/ sensitiveness**

Market position of a company shows the status of its products in relevant markets (Pettit et al. 2010; Razmi et al. 2017)). Market sensitiveness is the capability of a supply chain to interpret and react to actual demand. This characteristic helps to achieve agility in the supply chain (Christopher 2000).

iv. **Knowledge management and Information sharing**

Knowledge management and information sharing are the building blocks for the creation of a resilient supply chain (Pettit et al. 2013). Information sharing plays an important role in the reduction of risk thus making supply chain resilient and also helps in the reduction of the consequences of the bullwhip effect (Lee et al. 1997). The organizations lacking in information sharing are more prone to risk. For the reduction of supply chain risk, a supply chain community of associate members should be formed to assist the sharing of the right information (Jain et al. 2017).

v. **Public-private partnership**

Public-private partnerships may help in recovering from the post-disruption in the supply chains that arise due to the interpersonal relations and social capabilities (Li et al. 2017). Such a partnership can also be created by involving the partners during the co-creation processes and establishing trust.

4.3 Resistance

Supply chains should have the ability to resist against the various disruptions. Resistance phase is also referred as the disruption phase.

i. **Flexibility**

Supply chain flexibility is defined as the capability of modification, adaptation, and response to disruptive events (Purvis et al. 2016). It ensures the reediness of a supply chain during a disruption to minimize adverse effects by selecting an alternate course of action (Adobor and McMullen 2018). According to Razmi et al. (2017), flexibility is applied through flexibility in sourcing (ability to rapidly change inputs)

and flexibility in order fulfilment (ability to rapidly change outputs).

ii. **Collaboration/integration**

Supply chain collaboration is referred to as an ability to work with partners for effective planning and execution of supply chain operations for mutual benefits (Tukamuhabwa et al. 2015). Efficient collaboration stresses the importance of internal and external communication in order to achieve fast processes and high-quality results (Ehrenhuber et al. 2015). To identify and manage risk, a high level of collaboration is required between supply chain partners (Christopher and Peck 2004).

iii. **Redundancy**

Redundancy is the utilization of additional capacity or stocks to manage disruption, e.g., supply deficiencies (Christopher 2000; Christopher and Peck 2004). It allows firms to think about alternative options to recover from disturbances (Adobor and McMullen 2018). This ability to recover from disturbances “*is related to the development of responsiveness capabilities through redundancy and flexibility*” (Carvalho et al. 2014).

iv. **Supply chain network design/structure/orientation**

Understanding of structure or orientation is an important element to build a supply chain network for resilience (Tukamuhabwa et al. 2015). Supply chain orientation described as “*the implementation by an organization of the systemic, strategic implications of the tactical activities involved in the management of goods, services and information flow in a supply chain*” (Min and Mentzer 2004). Complex supply

chains are more vulnerable to disruption so the supply chain network designs should be optimized to overcome with the supply chain disruptions (Tang 2006; Soni et al. 2014).

v. **Risk and revenue sharing**

Risk and revenue sharing is imperative for collaboration among supply chain partners (Soni et al. 2014). The collaboration among partners provides a competitive advantage. Revenue sharing also encourages risk sharing among the supply chain members and thus reduces the overall risks of an individual member (Li et al. 2017).

vi. **Robustness**

Robustness is the ability of supply chain to anticipate and withstand advert conditions without suffering loss of function (Wieland and Wallenburg 2013; Shashi et al. 2020). A robust supply chain can function efficiently under disruptions by having alternative course of action or plan to implement (Purvis et al. 2016; Ali et al. 2017).

5 Results

Following the research methodology explained in Sect. 3, the results of the questionnaire and the discussion with the experts reflected on the relationship between the indicators (see Table 3). The Table 3 was further converted into an initial reachability matrix represented by 1 and 0 according to the value in the SSIM matrix, and after applying the transitivity characteristic the final reachability matrix is formed (See Table 4).

Table 3 SSI matrix representing the relationship between the SCR indicators

INDICATORS	MP	COLL	RS	VIS	FLE	SCRM	VEL	PPP	SCN	AWR	SUS	SEC	ROB	RED	AGL	IS
IS	V	X	V	A	V	V	X	V	V	V	V	V	V	V	V	X
AGL	X	V	X	A	A	O	A	A	A	X	A	X	X	V	X	
RED	A	V	V	A	V	O	V	V	V	X	X	X	X	X		
ROB	A	V	V	A	A	O	X	A	A	A	A	O	X			
SEC	V	V	V	X	V	A	V	X	X	O	O	X				
SUS	X	A	V	X	V	A	O	O	V	O	X					
AWR	O	X	V	X	V	V	O	V	V	X						
SCN	V	A	V	O	V	V	O	X	X							
PPP	V	X	V	O	V	A	V	X								
VEL	X	A	V	A	V	O	X									
SCRM	A	V	V	A	V	X										
FLE	A	V	A	A	X											
VIS	V	V	V	X												
RS	O	A	X													
COLL	X	X														
MP	X															

Table 4 Final reachability matrix representing the relationship between the SCR indicators

INDICATORS	MP	COLL	RS	VIS	FLE	SCRM	VEL	PPP	SCN	AWR	SUS	SEC	ROB	RED	AGL	IS
IS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
AGL	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RED	0	1	1	1	0	1	0	1	1	1	0	1	0	1	0	1
ROB	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0
SEC	0	1	1	1	1	1	0	1	1	1	0	1	0	1	1	1
SUS	0	1	1	1	0	1	0	1	1	1	0	1	0	1	0	1
AWR	0	1	1	1	0	1	1	1	1	1	0	1	0	1	1	1
SCN	0	1	0	1	0	0	0	1	1	1	0	0	0	0	0	1
PPP	0	1	0	1	0	0	0	1	1	1	0	0	0	0	0	1
VEL	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0
SCRM	0	1	1	1	0	1	0	1	1	1	1	1	0	1	1	1
FLE	0	1	0	1	0	0	0	1	1	1	0	1	0	0	0	1
VIS	0	1	1	1	0	1	0	1	1	1	0	1	1	1	1	1
RS	0	1	1	1	0	1	0	1	1	1	0	1	0	1	0	1
COLL	0	1	1	1	0	1	0	1	1	1	0	1	0	1	1	1
MP	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	1

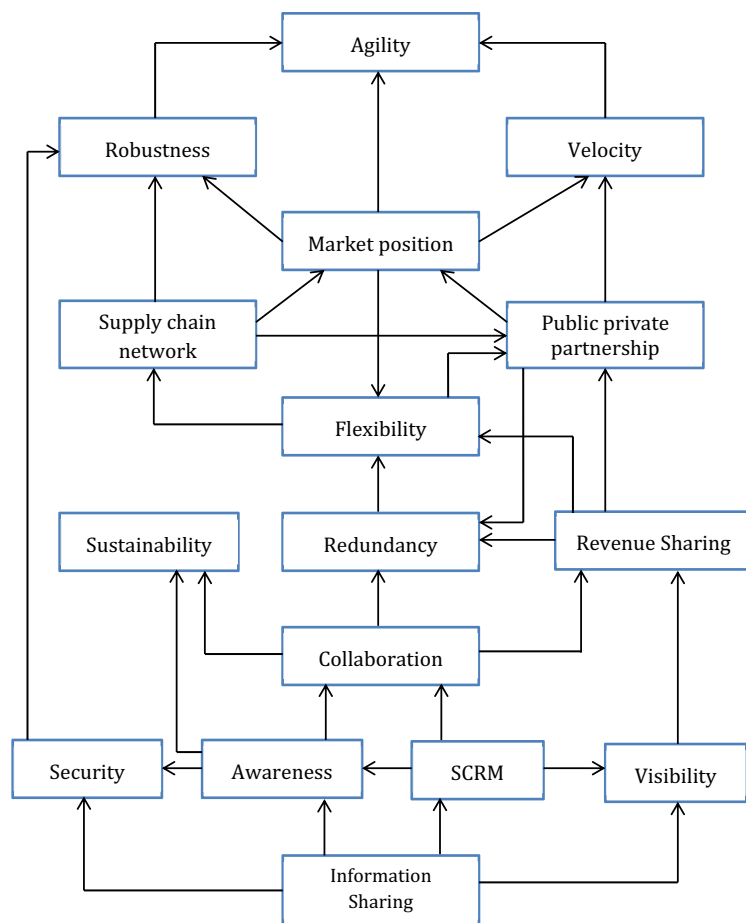
In the next step, different levels are present in the hierarchy of the SCR indicators. First step in the iteration is to get reachability and antecedent set from the final reachability matrix. Subsequently we will make intersection set. By glancing the reachability and intersection set level portioning is done. In Table 5 first stage of level portioning is showcased. In that for reachability and intersection set are same means it will come at first level. Similarly all the iteration will be carried out.

The partitioning table leads to the development of the ISM model shown in Fig. 2. This model reflects how an indicator depends on another indicator (the vertical relationship) and how two indicators are independent at adjacent levels (the horizontal relationship). In this diagram arc are showing the one way or two way direction, this is based on the expert opinion. Figure 2 is a preliminary network diagram and exhibits complex circular connections. This model is simplified using the BN approach (Fig. 3).

Table 5 Level portioning

Indicators	Reachability	Antecedent	Intersection	Level
IS	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16,	1,	1,	9
AGL	2,	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16,	2,	1
RED	2, 3, 4, 6, 8, 9, 10, 12, 14, 16,	1, 3, 5, 6, 7, 11, 13, 14, 15,	3, 6, 14,	6
ROB	2, 4, 10,	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16,	4, 10,	2
SEC	2, 3, 4, 5, 6, 8, 9, 10, 12, 14, 15, 16,	1, 5,	5,	8
SUS	2, 3, 4, 6, 8, 9, 10, 12, 14, 16,	1, 3, 5, 6, 7, 11, 13, 14, 15,	3, 6, 14,	6
AWR	2, 3, 4, 6, 7, 8, 9, 10, 12, 14, 15, 16,	1, 7,	7,	8
SCN	2, 4, 8, 9, 10, 16,	1, 3, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15,	8, 9,	4
PPP	2, 4, 8, 9, 10, 16,	1, 3, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15,	8, 9,	4
VEL	2, 4, 10,	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16,	4, 10,	2
SCRM	2, 3, 4, 6, 8, 9, 10, 11, 12, 14, 15, 16,	1, 11,	11,	8
FLE	2, 4, 8, 9, 10, 12, 16,	1, 3, 5, 6, 7, 11, 12, 13, 14, 15,	12,	5
VIS	2, 3, 4, 6, 8, 9, 10, 12, 13, 14, 15, 16,	1, 13,	13,	8
RS	2, 3, 4, 6, 8, 9, 10, 12, 14, 16,	1, 3, 5, 6, 7, 11, 13, 14, 15,	3, 6, 14,	6
COLL	2, 3, 4, 6, 8, 9, 10, 12, 14, 15, 16,	1, 5, 7, 11, 13, 15,	15,	7
MP	2, 4, 10, 16,	1, 3, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16,	16,	3

Fig. 2 ISM based Model for the supply chain resilience indicators



5.1 Assessing the resilience of supply chain – case studies

5.1.1 Background of the case companies

This section discuss about the case companies selected for assessment of resilience of supply chain. The case study is used to demonstrate, analyse and identify the improvement areas. Three case companies are considered for the practical implementation of the integrated ISM-BN approach presented in this study. All the three case companies are private limited manufacturing industries.

Case 1: Company A is certified by ISO/TS- 16949:2009, situated in the industrial area of Haridwar, India. The company uses aluminium ingots to cast components like lock body, tap body, lid body, and housing cover for the local automobile customers with a plant production capacity of 50 metric ton. The supply chain of the company is having four echelons as supplier, manufacturer, distributor and customer.

Case 2: Company B is also situated in the industrial sector of Haridwar, India. The company was established in 2010 and it is a firm and automobile supplier of tier-2. It is involved in manufacturing of the rubber part used for the

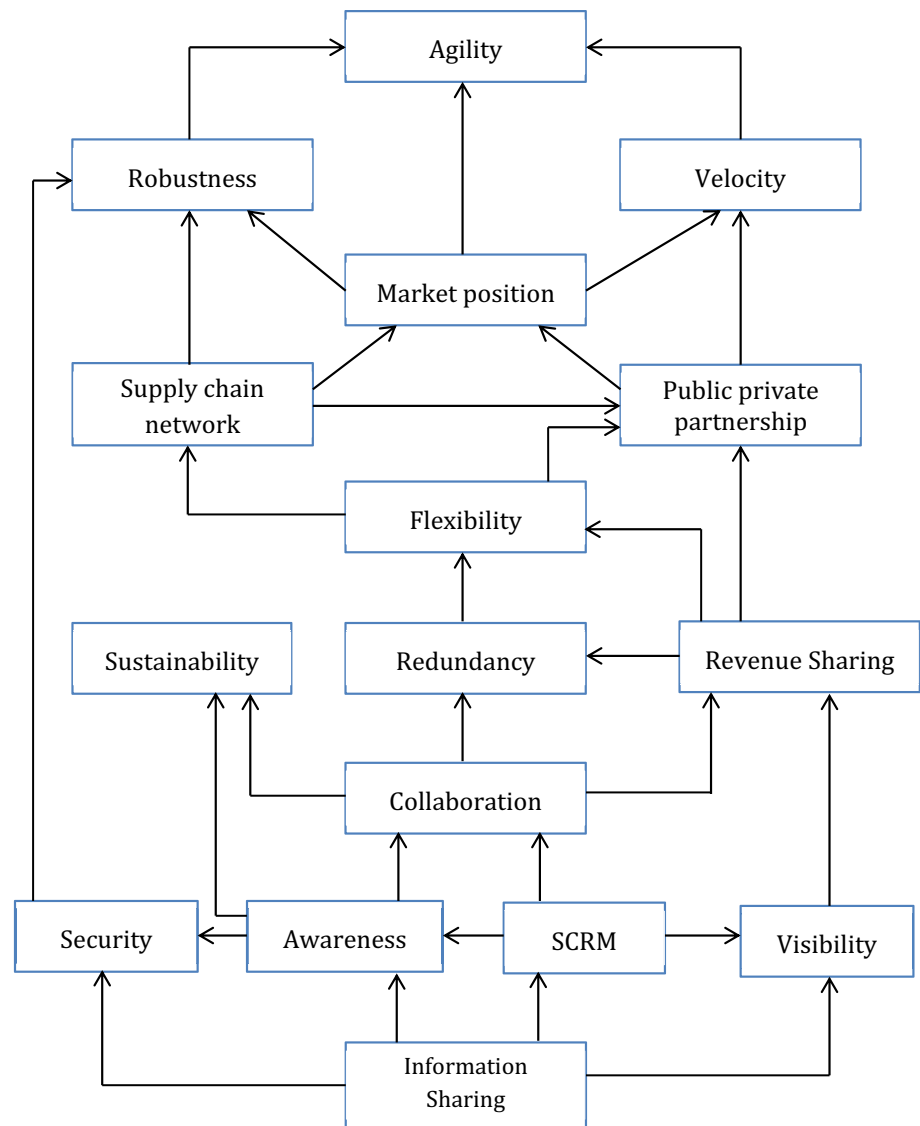
mirror assembly in a bike. The suppliers of the company are from National Capital Region Delhi and have their own local customers. The supply chain of the company involves supplier, manufacturer, distributor and customer.

Case 3: Company C was established in 1886 and is situated in Hyderabad, India. It pioneered several industries of national importance in India: steel, power, hospitality and airlines. Company has the supplier and the customers from all over the world. Supply chain network of the company consist of supplier, manufacturer and customer.

All the three manufacturing companies were performing well before the disruption caused by the Covid-19 pandemic. To assess the resilience of the case company, we explained the concept of SCR to the domain expert and an online questionnaire was distributed. Industry experts were also requested to complete the probability table for different indicators according to the current situation in their company. From the responses of industry experts, further Bayesian network analysis was performed.

Subsequent to building a BN, it is important to characterize a state space for every indicator for later probability assignment. The meaning of state for every indicator has been finished with the expert group. Every one of the factors

Fig. 3 Bayesian network for the supply chain resilience indicators



has two states i.e. Yes or No, which appears if the indicator is in the good or bad condition. For instance, the expert considered that information flow in the supply chain is either good or bad. BN demonstrating incorporates both qualitative and quantitative angles. The qualitative viewpoint comprises in building the coordinated non-cyclic system structure. The quantitative angle comprises in deciding the CPD's for the associated indicator, which expresses the needy connections between the indicators. CPT's are by and large used to measure the reliance of a Child Factor on its parent factors. Numerous kinds of information sources are as often as possible used to develops CPTs.

The information required in this study is received from domain experts having experience of real life supply chain network. The concept of CPT is explained to the experts and was asked to fill the entries of CPT's as per their experience.

An example of CPT associated with Child Factor Agility and its corresponding parent factor Revenue sharing, SC network, Flexibility is shown in Table 6. Based on the CPT value obtained from the experts, BN model is created as shown in Fig. 4. Table 7 shows the probability in percentage of different indicators.

Based on these conditional probabilities the BNs for all the three companies were created. Figures 5, 6 and 7 shows the BNs corresponding to the case company A, B, and C respectively.

5.2 Cross comparison of case study results

After formulating the BN for all three case studies, as a result some critical indicators were found. These critical indicator shows that the case company should work upon

Table 6 Conditional probability table for Agility

Market Position	Yes				No			
	Yes		No		Yes		No	
	Yes	No	Yes	No	Yes	No	Yes	No
Yes	1	0.7	0.8	0.4	0.8	0.3	0.3	0.01
No	0	0.3	0.2	0.6	0.2	0.7	0.7	0.99

these indicators to enhance their supply chain resilience. Table 8 shows the critical indicators for all three companies.

6 Discussion and implication

For the resilience of supply chain, there were sixteen indicators identified in three phases- Anticipation, Response & Recovery, and Resistance. The contextual relationship is established by industry experts that shows how one indicator affects another. Following the ISM methodology, the correlation between each indicators and their driving and dependence power was identified. The outcome of the ISM shows that agility is the key indicator to build a resilient

supply chain followed by robustness and supply chain velocity. The diagraph created by ISM is used as an input to the BN to analyse the strength of dependence. Based on the CPT's provided by the experts, a Bayesian network model is created which shows that robustness has the highest impact (probability of occurrence 0.96) on SCR. To illustrate the practical implication of the study, three case companies were selected. For each company, data related to the conditional probability was collected and individual Bayesian network was created. A cross comparison was also done to highlight the comparative resilience state and critical indicators of the three companies. The cross comparison results highlight that the agility, flexibility and velocity are the less focused indicators by the case companies.

Fig. 4 Bayesian network model

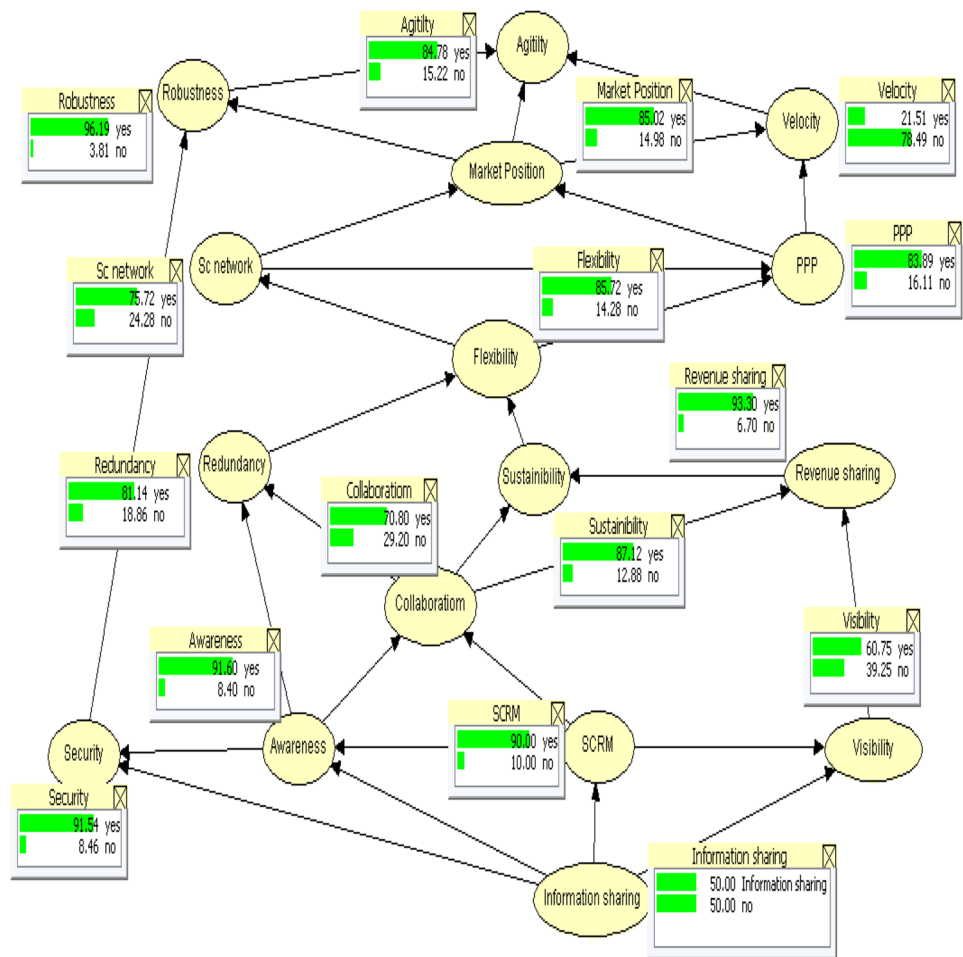


Table 7 Probability in percentage of different Indicators for Case Company A, B and C

Indicators	Assessment parameters	Probability in %					
		Case Company A		Case Company B		Case Company C	
		Yes	No	Yes	No	Yes	No
Visibility	Knowledge in transit from the manufacturer to customer	80	20	70	30	95	5
Awareness	Ability to forecast demand	80	20	65	35	75	25
Security	Cyber security	40	40	20	80	99	1
Sustainability	Effective use of the natural resources	70	30	80	20	85	15
SCRM	Employees training, leadership	90	10	85	15	80	20
Flexibility	Rapid adaption to the changes	80	20	60	40	40	60
Collaboration	Working with the other firms	20	80	60	40	30	70
Redundancy	Additional stock	20	80	50	50	30	70
SC Network	Relationship among the echelon of firms	90	10	75	25	80	20
Revenue Sharing	Distribution of profit and losses among partner	70	30	30	70	35	65
Robustness	Ability to resist the changes	80	20	80	20	75	25
Velocity	Speed of reaction	60	40	60	40	45	55
Agility	Rapid response	90	10	60	40	40	60
PPP	Partnership with the government	10	90	35	65	30	70
Market Position	Image of company in market	10	90	70	30	70	30
Information sharing	Data analysis-facilities, inventory cost, price and customers	90	10	70	30	70	30

Company A which is producing aluminium parts is having good hold on the anticipation phase of the disruption as information sharing; security and awareness are in the good condition. But it lacks at the response & recovery, and resistance phases. It can be visualised from the BN of the company that they need to work upon the collaboration, flexibility, velocity and agility indicators to sustain the disruption.

Company B which is producing the rubber part for the local distributors have issues in all the phases. Although company can predict the unwanted disruption in the supply chain but there is a need to improvement especially in the security indicator. Company has good hold on resistance phase as all indicators in resistance phase are in good condition except the redundancy. The company is lacking in response & recovery phases. It can be seen from BN that company need to work upon velocity and flexibility of the supply chain.

Company C manufactures and assembles the part of helicopter and fighter plane. Company doesn't have strong participation in resistance and response & recovery phase, but has good anticipation capability. All the indicators in anticipation phase are in good condition. To make their supply chain resilient, they need to work upon response & recovery, and resistance phases. In particular, the company needs to work upon revenue sharing, collaboration in resistance phase and velocity, flexibility and agility in the response & recovery phase.

This study combines the existing literature and expert reviews to assess the supply chain resilience of case companies facing the Covid-19 pandemic disruption. The Covid-19 pandemic has resulted in scarcity of finished products due to the limited supply of raw material during the lockdown. According to Tarigan et al. (2021), one of the reasons is bullwhip effect in the manufacturing companies supply chain. The industries should diversify their operations in different regions so that they could be able to operate at part capacity where there is less impact and severity of virus spread. In the existing literature of Supply chain resilience, very few studies have assessed the interdependency among the indicators using ISM and Bayesian alone. This study has combined the ISM and BN approaches to model the expert knowledge as well as to analyse the strength of interdependency. The results highlight several areas where case companies need to work to enhance the resilience of their supply chain. The implementation and performance measurement of the supply chain resilience is always a concern for the decision makers to deal with the disruptive situations. Manufacturing enterprises need to rethink how they manage their operations in order to deal with the disruptive situations such as the current Covid-19 pandemic. It can be analysed from the results that a company should focus on all the three phases (anticipation, response & recovery and resistance) in order to become resilient.

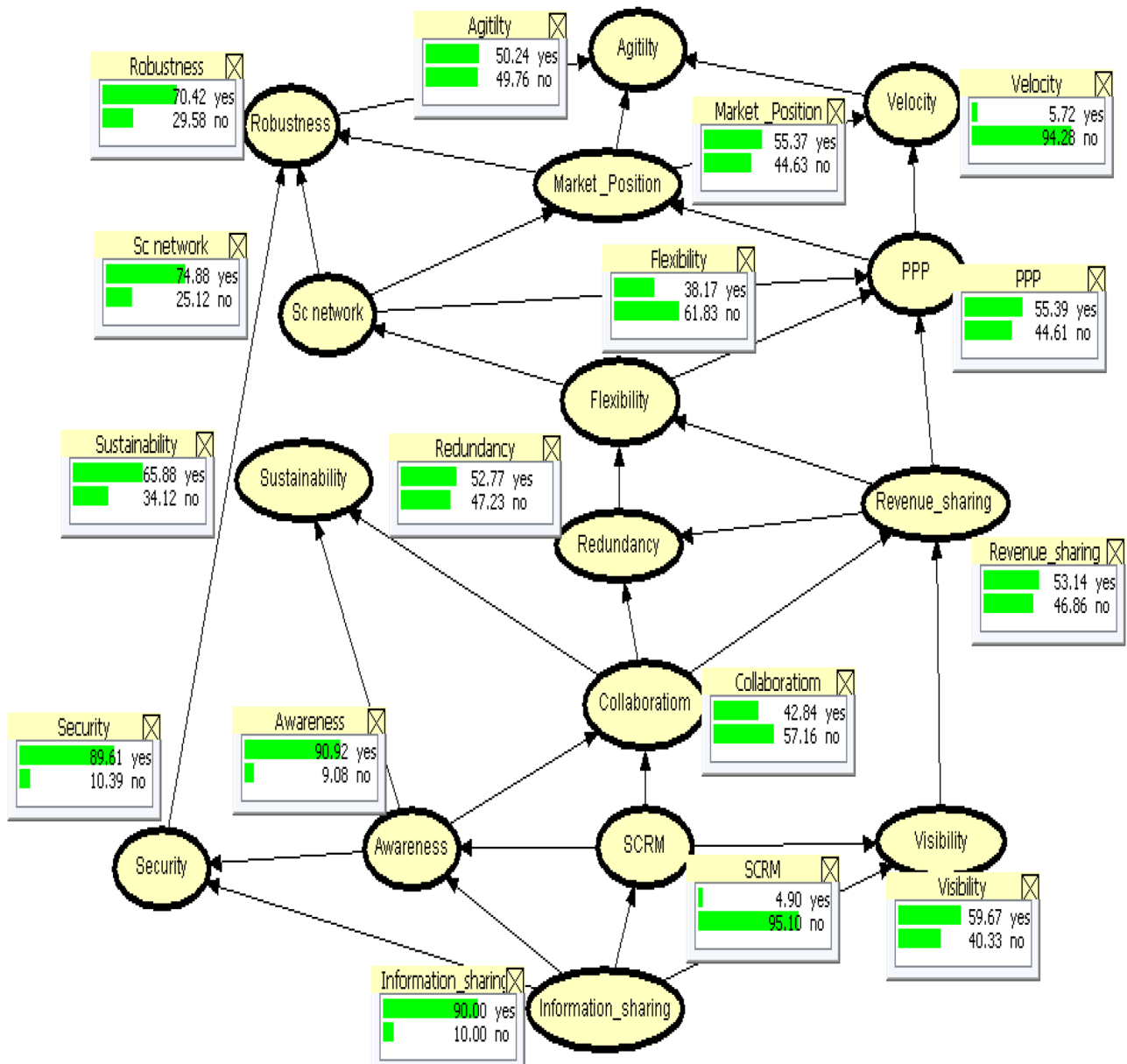


Fig. 5 Bayesian network model for case study A

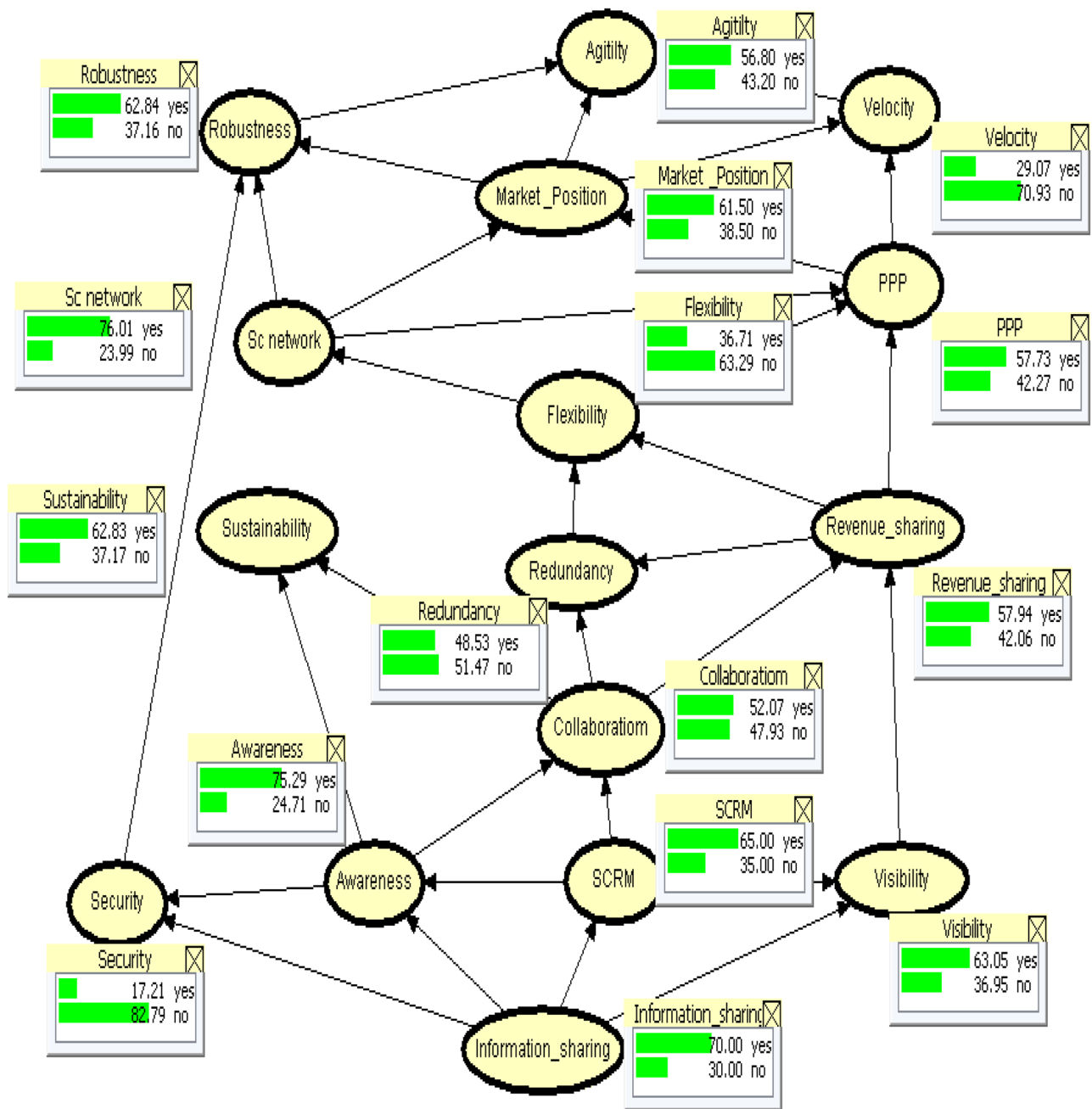


Fig. 6 Bayesian network model for case study B

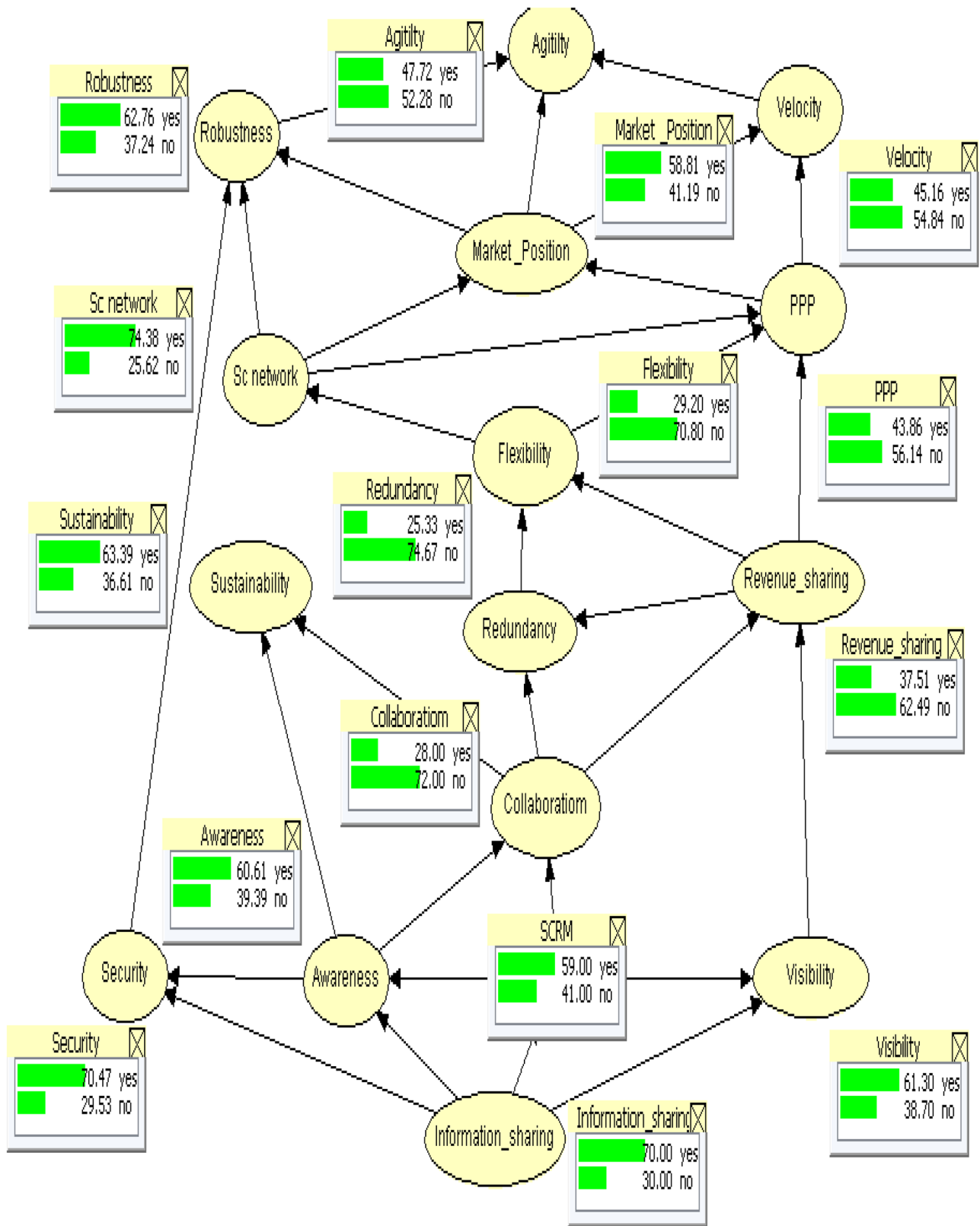


Fig. 7 Bayesian network model for case study C

Table 8 Critical indicators for all three case studies

Indicators	Case A	Case B	Case C
Information sharing			
Agility	×		×
Redundancy		×	
Robustness			
Security		×	
Sustainability			
Awareness			
SC Network			
Public-private partnership			
Velocity	×	×	×
SCRM	×		
Flexibility	×	×	×
Visibility			
Revenue sharing			×
Collaboration	×		×
Market position			

7 Conclusion and future research directions

The purpose of this study is to assess the resilience of a supply chain in absorbing the disruption impacts such as the current Covid-19 pandemic by integrating the Interpretive Structure Modelling with the Bayesian network approach. For developing the assessment model, indicators for supply chain resilience were identified from the extant literature and with the help of academic and industry experts. The identified indicators were then categorized into three phases—anticipation, response & recovery and resistance. ISM is used to identify the interrelationship among all SCR indicators, while BN is used to identify the strength of the dependency based on the probability distribution. From the ISM method, driving and dependency powers of the indicators were analysed. It was observed that “Information Sharing” has the highest driving power among all the sixteen indicators. The practical implication of the proposed approach is demonstrated by considering case of three Indian manufacturing companies facing the disruption caused by Covid-19 pandemic. All case studies have different critical indicators which were calculated on the basis of their conditional probability. The result of this study will be helpful to decision makers/supply chain managers in developing the mitigation strategies in a supply chain against the disruption events and helps to improve its performance by assessing its resilience and focus on the critical indicators.

The study is having few limitations. Considering the Indian scenario, the Covid-19 pandemic is still continuing with unpredictable new variants. The results and discussion presented here are based on the data available currently and

may change in future. Nevertheless, this study would be helpful for the industries to focus on the resilience parameters to overcome the disruptive situation. The research conducted in this paper was exploratory in nature based on the experience of manufacturing industry experts; therefore lacks on a clear industrial background. As a future scope empirical studies can be conducted for industry specific environment. The model constructed in this study was created using ISM and BN methodology that is based on the expert opinion. To make this model more realistic and to improve the integrity of the Bayesian network model, opinion of diverse field experts should be incorporated.

Declarations

Competing interests The authors have no relevant financial and competing interests to declare.

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