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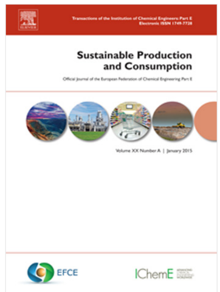

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A Fuzzy Approach to Analyzing the Level of Resilience in Manufacturing Supply Chains

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Abstract

Achieving sustainability and resilience in supply chains is a topic of contemporary interest to supply chain practitioners of the decade. Resilience is a technological capability that enables the supply chain to manage and mitigate disruptions. A major challenge lies in the measurement of supply chain resilience. Resilient Fuzzy Index (*RFI*) is proposed in this research to measure the level of resilience of firms. Also, Performance Fuzzy Index (*PFI*) is developed in this study that aids in identifying critical attributes affecting resilience in supply chains. Calculation of *RFI* and *PFI* could assist top management in evaluating resilience capabilities of the supply chain for taking strategic level decisions. The proposed framework has also been evaluated in an actual electronics manufacturing company in India. Euclidian distances were calculated using the methodology and the status of the resilience of the supply chain of the case electronics manufacturing company is found to be matching with the *'Extremely Resilient'* status. Sensitivity analysis was also conducted and the results of the same show that there is a full possible shift from *'Extremely Resilient'* to *'Definitely Resilient'* level, by improving the performance rating of the attributes to their maximum possible values. And from the results of the case study, managers can measure, compare, and improve the level of resilience of their supply chains.

Keywords: Technological capability; Risk management; Supply chain resilience; Electronics manufacturing.

1. Introduction

Increased globalized competitions, lean and agile operation orientations, ever increasing expectation from customers, shrinking product life cycles, etc., has made management of supply chains a great challenge for managers (Reinhorn, 2013). Apart from that, supply chains are subject to lot of risks (Benjamin *et al.*, 2015) and variability amplification due to bullwhips (Mangla *et al.*, 2015). These risks can occur at *four* levels, (i) *process and value stream related risks*, (ii) *assets and infrastructure related risks*, (iii) *organizational and inter-organizational risks* and (iv) *risks related with the environment* (Christopher, 2004).

Disruptions can be defined as major breakdowns in the production or distribution nodes constituting a supply chain. Resilience is defined as the ability of the system to return to its original state after being disturbed (Christopher and Peck, 2004). In supply chain context, it is the technological capability to manage and mitigate from disruptions (Rajesh, 2019b). In other way, resilience can be understood as the ability to manage risks, i.e. being better positioned than competitors to deal with disruptions (Sheffi, 2005). Apart from that, resilience to disasters is the technological capability of a supply chain system to reduce the probabilities, consequences and time to recover from disruptions (Handfield, 2007). Achieving sustainability and resilience in supply chains is a topic of contemporary interest to supply chain practioners of the decade (Rajesh, 2018a; Rajesh, 2019a).

Bruneau *et al.* (2003) introduced the concept of a resilience triangle. The resilience triangle represents a measure of both the loss of functionality of a system after a disaster and the amount of time it takes for the system to return to normal performance levels (Tierney and Bruneau, 2007). Resilient supply chains have the ability to adapt to both positive and negative influences of the environment. Hence, resilience can be a distinct source of sustainable competitive advantage (Hamel and Valikangas, 2003). Environmental as well as economic considerations are to be addressed for bringing sustainable competitiveness (Jayant *et al.*, 2012). Constructing resilient supply chains have some important questions to keep in mind as, (i) what are the parameters contributing to supply chain resilience? (ii) what is the measure of level of resilience of a supply chain? (iii) how do companies compare their performances in resilience? This research has been conducted to answer these questions.

Datta *et al.* (2007) presented an agent-based framework for improving supply chain flexibility and resilience by studying multi-product, multi-country supply chains subject to demand variability, production, and distribution capacity constraints. Craighead *et al.* (2007) showed an empirical research design for classifying the severity of supply chain disruptions based on *three* specific supply chain design characteristics (*density*, *complexity*, and *node criticality*). Pettit *et al.* (2013) formulated a conceptual framework for measuring supply chain resilience in consideration of various traits imparting resilience and formulated an assessment tool for same. Azevedo *et al.* (2013) proposed an eco-resilient index for supply chains aimed at reducing the energy consumptions making the supply chain green, at the same time increasing its competitiveness. Soni *et al.* (2014) formulated a modeling approach for gauging supply chain resilience employing graph theory and matrix approaches. A detailed review of literature on recent works in supply chain resilience is conducted and is presented in Table 1.

Literature review on resilient supply chains indicate that an index that describes the level of resilience closeness of a supply chain based on various strategic and attribute level considerations or an index that describes the critical factors affecting the resilience of supply chains considering various strategies and attributes of resilience are not found till date. From the literature, it is also seen that there is need for matching the level of resilience of the supply chain with prefixed linguistic labels. This can assist managers to knowing the exact level of resilience of their supply chains for improvement and to compare their performances with that of the competitors. Also, it is seen that most of the strategies and attributes contributing to the resilience performances of the supply chain are less tangible and can be measured using linguistic labels. Fuzzy set theory can be best used in situations of cognitive uncertainties and in group decision-making environments. These needs have provided the motivation for the present research.

A framework of policies, strategies and attributes is to be constructed for the evaluation of the level of resilience. In general, electronics manufacturing firms have to consider the following stratagems for effectively implementing resilience in their supply chains: *Supply chain risk assessment* (Christopher and Peck, 2004), *Strategy focused collaboration and control* (Christopher, 2004), *Agility and responsiveness in supply chains* (Lee, 2008), *Flexible supply chains* (Ponomarov and Holcomb, 2009), *Supply chain risk management culture* (Christopher and Peck, 2004). The details of the strategies and attributes considered for a resilient supply chain with characteristic focus on electronics manufacturing firms along with relevant literature are said in Table 2 and an illustrative outlook of those is shown in Figure 1. This paper is further organized as follows. The methodology for measuring and improving the level of resilience capabilities of the firm is discussed in Section 2. The assessment of the proposed framework in a real case electronics company is elaborated in Section 3. Section 4 discusses on the results and research implications from the case supply chain standpoint. Conclusions and scope of future works are expounded in the next section.

2. Methodology

It can be seen that many of the attributes for resilience assessment are qualitative in nature, which can be best described subjectively using linguistic terms. Subjective decision-making models can be better used in such situations (Sabu *et al.*, 2018). Grey theory and Fuzzy set theory are widely employed to problems dealing with vague or imprecise data (Lin *et al.*, 2006; Rajesh, 2018d). Fuzzy logic has been used in a wide variety of management decision making applications (Radivojević and Gajović, 2014) and for the proposal of fuzzy indices

(Lin *et al.*, 2006). In this research, we have developed a supply chain resilience evaluation model based on fuzzy logic. A resilient index is formulated by considering the strategies and attributes imparting resilience in a supply chain. Fuzzy scoring method is used for evaluating the level of resilience in a supply chain. Also, it is possible to suggest how far the supply chain needs to improve its capabilities to attain a desired level of resilience. The flow chart showing the procedure is shown in Figure 2. The method of calculation of Resilient Fuzzy Index (*RFI*) and matching the *RFI* with linguistic ratings is shown as follows:

2.1 Formation of a committee of supply chain analysts

A group of supply chain analysts of the company, experts in the field of supply chain management were selected to form a committee to set the required level of resilience for the supply chain. Through careful analysis of the performance needs of the company, analyst could judge the required level of resilience to be achieved.

2.2 Linguistic scale of assessment

The rating scales for the attributes imparting resilience and the assigned weighing are to be decided. Also, the fuzzy numbers associated with each rating scale must be assigned. These linguistic assessments can be converted into fuzzy values and corresponding membership functions can be obtained. Triangular membership functions were taken for associating with linguistic ratings and weightings.

2.3 Calculate the RFI of the supply chain

Suppose the committee is having *m* assessors, i.e. A_t, $t = 1, 2, 3\ldots, m$, is conducting the resilience assessments. Let F_j, $j = 1, 2, 3\ldots n$, corresponds to the factors imparting resilience, let $X_{jt} = (a_{jt}, b_{jt}, c_{jt})$ be the triangular fuzzy numbers corresponding to the linguistic average rating given by the committee A_t, and let $Y_{jt} = (x_{jt}, y_{jt}, z_{jt})$ be the triangular fuzzy numbers corresponding to the average score obtained for the weight of factors, i.e.

$$X_j = (a_j, b_j, c_j) = \frac{X_{j1}(+)X_{j2}(+)\ldots(+)X_{jm}}{m} \quad (1)$$

$$Y_j = (x_j, y_j, z_j) = \frac{Y_{j1}(+)Y_{j2}(+)\ldots(+)Y_{jm}}{m} \tag{2}$$

Table 1: Recent literature on resilience in supply chains

Sl. No.	Author(s)	Nature of Work	Problem Addressed	Key Findings	Remarks
1.	Margolis *et al.* (2018)	Multi-objective optimization	Presented a multi-objective network design model and an optimization-based decision support methodology for supply chain architects	Evaluated the trade-off between total network cost minimization and maximizing overall supply chain network connectivity	By evaluating a collection of solutions with different cost and connectivity values, the best network configuration can be selected
2.	Chen *et al.* (2017)	Mathematical modelling	Proposed a unified framework for evaluating resilience that internalizes design inputs and is flexible to varying degrees of data availability	The framework captures risks involved in the supply, the demand, the firm and the external environment	Method using buyer-supplier relationships in supply chains is designed to model node interdependencies
3.	Akkermans and Van Wassenhove (2018)	Case based study	Discussion on how supply chain tsunami unfolds over time	Each type of tsunami focuses on parts of the supply chain periphery, where the signals of developing tsunami can be observed	The notion of supply chain tsunamis was linked with the need to reviving strategic operations and supply chain management
4.	Nabeel *et al.* (2018)	Case based study	Study of resilience for tantalum supply chain	Quantification of the unaccounted tantalum supply sources and its impact on the resilience.	Four of the resilience promoting factors were analyzed for the supply chain
5.	Lücker and Seifert (2017)	Mathematical modelling	Building resilience through inventory, dual sourcing, and agility	Effect of reducing inventory with dual sourcing and agility is investigated	The production rate of dual sources can decrease in the disruption time for long disruption times
6.	Cheng and Lu (2017)	Empirical study	Study of trajectory and absorptive capacity influencing supply chain resilience	Improving proactive and reactive dimension of supply chain resilience	Trajectory and resource-based perspectives were used to develop hypothesis

Sl. No.	Author(s)	Nature of Work	Problem Addressed	Key Findings	Remarks
7.	Pavlov *et al.* (2018)	Fuzzy-probabilistic model	Measuring supply chain resilience	Incorporating ripple effect and structure reconfiguration in resilience measurement	A supply chain design resilience index was proposed and its application was demonstrated
8.	Wang *et al.* (2018)	Mathematical model based on network theory	Proposal of a theory for the management of supply network for resilience	The model considers the information of the health state of firm and the knowledge of disruptions over the entire network	A tool was developed for the prediction of disruption and its propagation over the supply network
9.	Liu *et al.* (2018)	Empirical study	Study the relationship between supply chain resilience and firm performance	Risk management culture has positive impacts on agility, integration and supply chain re-engineering	Risk management culture has a great influence over supply chain performance
10.	Chowdhury and Quaddus (2017)	Empirical study	Conceptualization and scale development for resilience	Resilience is a construct of three dimensions: proactive capability, reactive capability and supply chain design quality	Scale for resilience can predict supply chain operational vulnerability and supply chain performance
11.	Ali *et al.* (2017)	Systematic literature review	Analyzed the concept of supply chain resilience within a concept mapping framework	Classifying different features of resilience to establishing relationships and interactions between them	Addresses the need for conceptual clarity in supply chain resilience
12.	Brusset and Teller (2017)	Empirical study	Achieving resilience through mapping relations between practices, resources, and processes	The perception of supplier risk helps motivate the supply chain managers to achieving higher resilience	The perception of external risks to a supply chain reduces the effort of deploying external capabilities to achieving resilience

Sl. No.	Author(s)	Nature of Work	Problem Addressed	Key Findings	Remarks
13.	Jain *et al.* (2017)	Empirical study	Developing a hierarchy-based model for supply chain resilience	Organizations can enhance their resilience potential by modifying their strategic assets	Explain the dynamics between various enablers to achieving resilience
14.	Tukamuhabwa *et al.* (2017)	Case based research	Investigate supply chain resilience in a developing country context and to provide theoretical insights to the concept of resilience	The threats of disruption, resilience strategies and outcomes are inter-related in complex, coupled and non-linear ways	The inter-relations are explained by the political, cultural and territorial embeddedness of the supply network
15.	Macdonald *et al.* (2018)	Simulation based study	Developing a three-component framework aimed to building better theories in supply chain resilience	The framework is analyzed through structured experimental design with discrete-event simulations	The factors of shock inter-arrival time, supply chain connectivity and buffer stocks were considered
16.	Donadoni *et al.* (2018)	Empirical study	Investigated the relationship between product complexity, disruption and performance using resilience capabilities as moderating variables	Product complexity increases the probability of disruption occurrence that affects the plant performance	Resilience allows supply chains to reducing the harmful effects of a disruption
17.	Ribeiro and Barbosa-Povoa (2018)	Systematic literature review	Conducted study on supply chain resilience definitions to proposing a framework	Research gaps and future directions in quantitative models for supply chain resilience is piloted	Relationships among supply chain resilience and supply chain risk was analyzed
18.	Namdar *et al.* (2018)	Mathematical modelling	Investigate on the sourcing strategies to achieving supply chain resilience under disruptions	Single and multiple sourcing, backup supplier contracts, spot purchasing, and collaboration and visibility were considered for study	Buyer's warning capability can play a vital role in enhancing supply chain resilience

Sl. No.	Author(s)	Nature of Work	Problem Addressed	Key Findings	Remarks
19.	Rajesh (2018a)	Conceptual study	Concept of sustainable-resilient supply chains is proposed	Decoupling point positioning plays a major role in determining the focus on sustainability and resilience	The evolutionary sequence of supply chains was studied with respect to the positioning of partition line
20.	Rajesh (2018b)	Conceptual study	Concept of pseudo resilient supply chains is proposed	Relations to supply chain vulnerability, resilience and pseudo resilience was identified	The traits of pseudo resilience in supply chains were identified and a disruption analysis is done
21.	Rajesh (2018c)	Grey decision-making model	The barriers to resilience in supply chains were quantified	Barriers to resilience were identified and grouped into classes based on their importance	Measuring and managing the barriers to resilience can reduce the vulnerabilities in supply chains
22.	Rajesh (2019)	Grey prediction modelling	Social and environmental risk management in resilient supply chains was studied	A grey- Verhulst model has been implemented to study the drivers of social and environmental risk management	Model can be used to study periodical data with saturated sigmoidal tendances
23.	Li *et al.* (2017)	Simulation study	Effect of information sharing on supply chain resilience was studied	Performance comparison for three ordering policies were studied for a three echelon supply chain	The role of information sharing become significant during shocks or disruptions

Table 2: Strategies and attributes for building resilience

Sl. No	Strategy	Attributes	Relevant Literature	Remarks
A.	**Supply chain risk assessment**		Wieland and Wallenburg (2012); Punniyamoorthy *et al.* (2013)	Knowledge of the network of suppliers to the downstream customers.
1.		Supply risk	Chen *et al.* (2013); Govindan and Jepsen (2015)	Companies with multiple time zones and regulation have severe supplier risks.
2.		Process risk	Zhao *et al.* (2013); Dekker *et al.* (2013)	Risk assessments are essentially to be carried for more complex processes.
3.		Demand risk	Samvedi *et al.* (2013); Bish and Chen (2015)	Demand risk occurs when demands exceed or fall short of expectations.
4.		Control risk	Jacxsens *et al.* (2010); Power (2011)	The risks that exert control over processes should be estimated.
5.		Environmental risk	Wang *et al.* (2012); Dües *et al.* (2013)	Pressures or changes in environmental conditions ensuing from human activities.
6.		Vulnerability checks	Chen and Larsen (2010); Liu and Zhuang (2013)	Reviews enhance business visibility to risks for reacting to them effectively.
B.	**Strategy focused collaboration and control**		Ross, F. F. (2013); Hines (2014)	Increases risk hedging capabilities of supply chains.
1.		Planning for contingencies	Danese (2011); Chopra and Sodhi (2012)	Identifying back-up technologies, developing alternate supply chain strategies.
2.		Connectedness	Wisner *et al.* (2015); Stadtler (2015)	Connectedness is the behavior to bend together for reducing wasteful services
3.		Collaborative Planning, Forecasting, Replenishment (CPFR)	Mentzer *et al.* (2011); Chen *et al.* (2013)	Interactions with partners in planning, forecasting and replenishment.
4.		Supply chain intelligence	Kwak and Gavirneni (2014); Sc[illegible] and Parola (2015)	Increasing the level of knowledge created and shared among partners.
C.	**Agility and responsiveness in supply chains**		Wieland and Wallenburg (2012); Williams *et al.* (2013)	Presence of agile partners in supply chain enhances the resilience capabilities.
1.		Visibility	Xiao and Qi (2008); Lee *et al.* (2014)	Visibility is having a vivid view of supply chain inventories and other settings.
2.		Velocity	Jüttner and Maklan (2011); Choi *et al.* (2013)	Pipeline times should be reduced to respond to fluctuating demands or supplies.
3.		Abolition of functional silos	Bakker (2012); New (2015)	Second guesses due to functional silos restrict proper communication.

Sl. No	Strategy	Attributes	Relevant Literature	Remarks
4.		Strong supply base	Pero *et al.*(2010); Ziggers and Henseler (2015)	Having a lead supplier along with alternative suppliers available at emergency.
5.		Reduction of non-value added time	Paul *et al.* (2010); Sigari and Clark (2013)	Non-value added time related each supply chain processes need to be reduced.
D.	**Flexible supply chain**		Singh and Sharma (2014); Blome *et al.* (2014)	Make the supply chain capable of responding to fluctuating demands.
1.		Standardization	Lee (2011); Costinot *et al.* (2013)	Inventory reduction by use of interchangeable and standard parts in products.
2.		Parallel processes	Droge *et al.* (2012); Serdarasan (2013)	A concurrent process instead of sequential processes reduces bottlenecks.
3.		Postponement verdicts	Merschmann and Thonemann (2011); Schwartz and Voß (2014)	Delaying manufacturing of a product until exact specifications are available.
4.		Supply chain efficiency	Chopra and Sodhi (2012); Droge *et al.*(2012)	Just-in-time production systems and logistic supplier nets improves efficiency.
E.	**Supply chain risk management culture**		Ponomarov and Holcomb (2009); Wieland and Wallenburg (2012)	Risk assessments should be made a formal part of all decision making situations.
1.		Aligning tasks	Briano *et al.* (2009); Thomas *et al.*(2011)	Creating awareness among employees for aligning their work.
2.		Continuity management	Vahdani *et al.* (2011); Blome *et al.* (2013)	Risk management tasks are to be enhanced to continuity management practices.
3.		Distributed power	Laanti (2013); Hoejmose *et al.* (2013)	Authorizes power to each and every employee to act in cases of emergency.
4.		Disruptions conditioning	Goswami *et al.* (2013); Pettit *et al.* (2013)	Build long-term strategy planning along with responses to short-term disruptions.

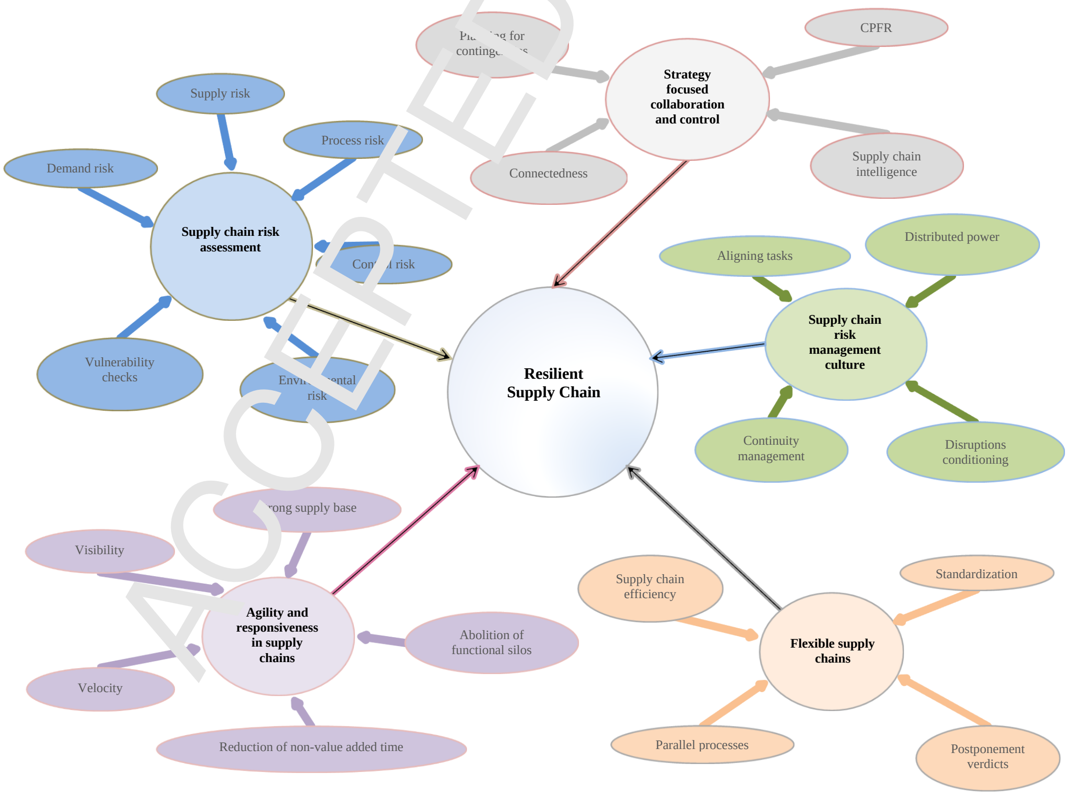

Figure 1: Building blocks of resilience

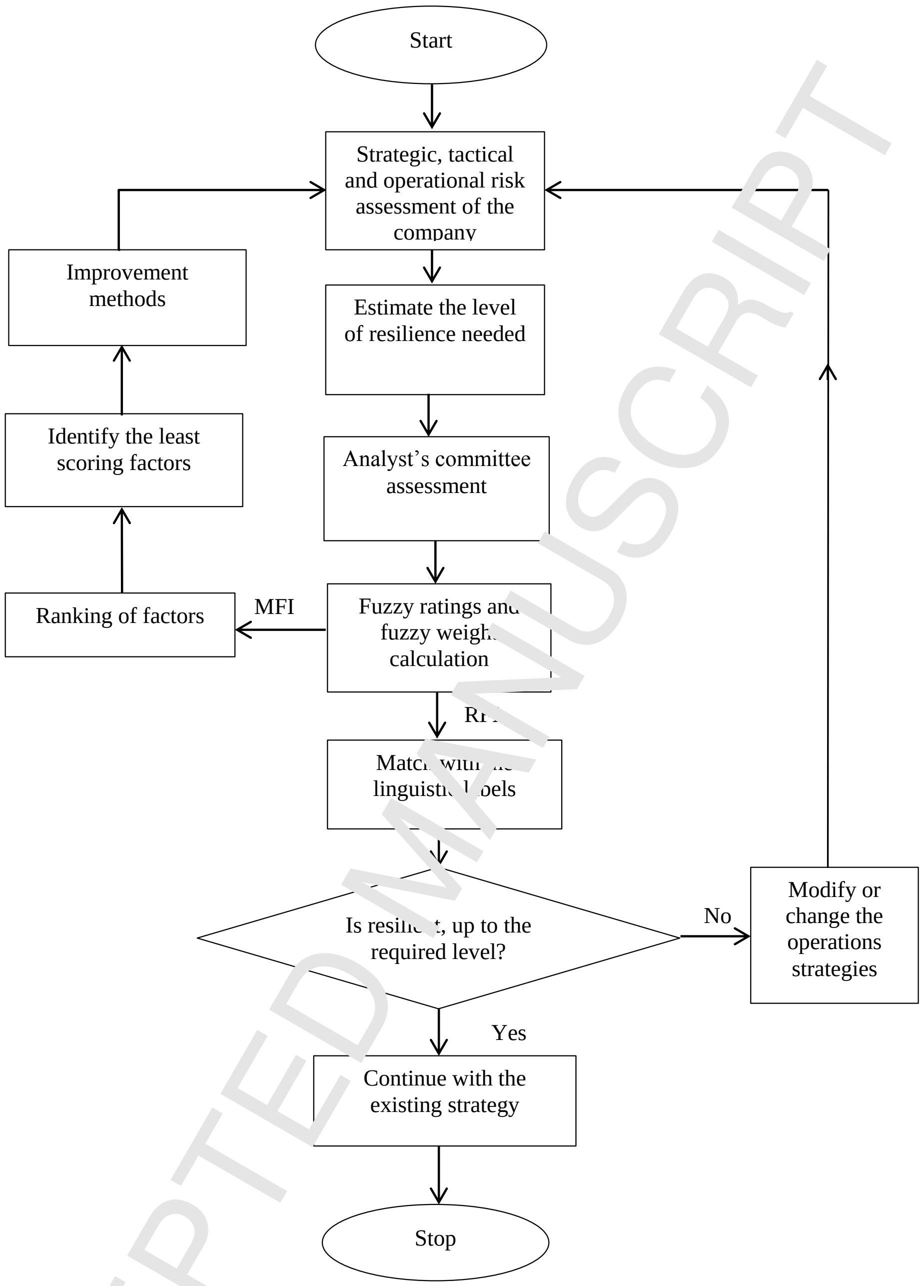

Figure 2: Flow chart representation of resilience assessment and improvement

Resilient Fuzzy Index (*RFI*) consolidates the fuzzy ratings and the fuzzy weights of all the factors influencing resilience. Let $X_j, j = 1, 2, 3\ldots, n,$ denote average fuzzy rating and Y_j, $j = 1, 2, 3\ldots, n,$ denote the average fuzzy weight given to factor j by the assessment committee, then *RFI* is calculated as follows,

$$RFI = \sum_{j=1}^{n}(Y_j(.)\,X_j)/\sum_{j=1}^{n}Y_j \tag{3}$$

The membership function of *RFI* as shown in Figure 3 can be represented as follows;

$$M_{RFI}(x) = \begin{cases} 0 & \text{if } x \le a \\ \frac{(x-a)}{(b-a)} & \text{if } a < x \le b \\ \frac{(c-x)}{(c-b)} & \text{if } b \le x < c \\ 0 & \text{if } x \ge c \end{cases} \tag{4}$$

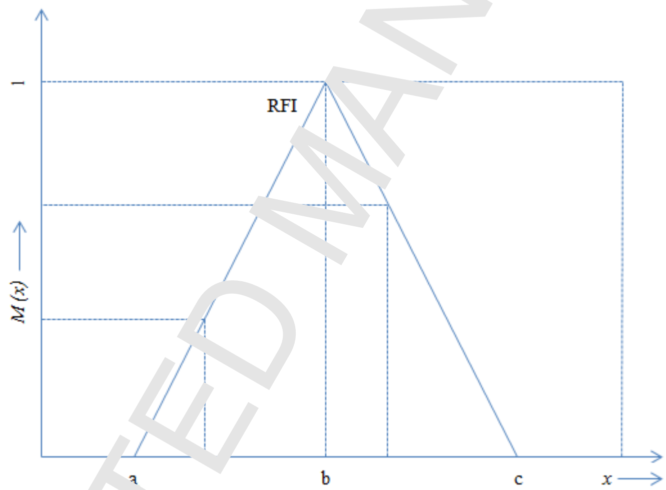

Figure 3: Triangular Membership function for RFI (*a, b, c*)

2.4 Matching the fuzzy rating with a linguistic expression

After calculating *RFI*, membership function of the *RFI* is to be matched with some natural linguistic set of resilience labels. In this research, we use the Euclidian distance method to identify where actually does the resilience level match with the linguistic label. Assume the linguistic expression level of resilience is the set RS_i. Let the membership functions be M_{RFI} and M_{RSi} for *RFI* and linguistic level *i*, respectively.

The distance between M_{RFI} and M_{RSi} can be calculated as,

$$D(RFI, RS_i) = \left\{\sum_{x\in p}(M_{RFI}(x) - M_{RS_i}(x))^2\right\}^{1/2} \quad (5)$$

where, $p = \{x_0, x_1, \ldots, x_m\} \in [0,1]$, such that $0 = x_0 < x_1 < \ldots < x_m = 1$. For ease of calculation, p is taken as, $p = \{0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1\}$. After calculating the Euclidian distance, the linguistic expression with the shortest distance is identified to be as the level of resilience closeness of the supply chain.

2.5 Rating the performance indices of resilient factors

Determination of resilience level helps in identifying the hindrances in attaining required level of resilience. In order to improve the level of resilience, a Performance Fuzzy Index (*PFI*) has been developed that combines both the performance rating and weights of attributes contributing to resilience. For the calculation of *PFI*, if the importance weights (Y_j) are directly taken, it will neutralize performance ratings. So a transformation [$(1, 1, 1)\ (-)\ Y_j$] is made to reduce the impact of weights Y_j. A Merit Fuzzy Index (*MFI*) is calculated that indicates the contribution of each resilient attribute towards supply chain resilience as,

$$MFI_j = X_j(.)\left[(1,1,1)(-)Y_j\right] \quad (6)$$

As the fuzzy numbers do not always give comparable sets, they should be ranked. The fuzzy numbers are ranked here by the left and right scoring method (Chen *et al.*, 2003; Lin *et al.*, 2006), as it considers the absolute location of each fuzzy number along with which it keeps the ranking order. The fuzzy minimizing and maximizing sets are respectively defined as,

$$M_{max}(x) = \begin{cases} x, & 0 \leq x \leq 1, \\ 0, & otherwise, \end{cases} \quad (7)$$

$$M_{min}(x) = \begin{cases} 1-x, & 0 \leq x \leq 1, \\ 0, & otherwise, \end{cases} \quad (8)$$

Let M_{PFI} be the triangular membership function for a fuzzy number *PFI* defined as $M_{PFI}: R \rightarrow [0,1]$. The left and right scores for a triangular fuzzy value, *PFI* is obtained using the left right scoring method that is shown in Figure 4.

Then the right and left scores are obtained respectively, as

$$M_R(PFI) = \sup_x [M_{PFI}(x) \wedge M_{max}(x)], \quad (9)$$

$$M_L(PFI) = \sup_x [M_{PFI}(x) \wedge M_{min}(x)], \quad (10)$$

where $\wedge$ is a minimal operator. The total score is obtained by combining the left and right scores, i.e. $M_T(PFI) = [\, M_R(PFI) + 1 - M_L(PFI)]/2$ (11)

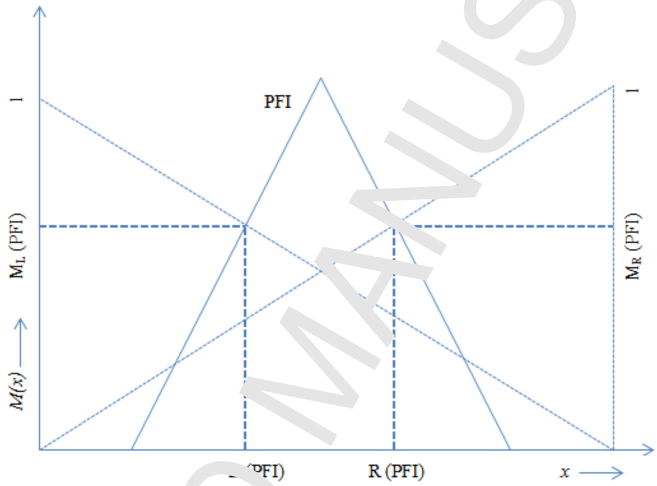

Figure 4: Left and right scores for PFI

3. A real case company example

The proposed framework in this research was tested in an electronics manufacturing company '*XYZ*' in India. *XYZ*'s global supply chain has raw material extraction and processing on its one end and component manufacturing and final product assembly at the other. A global manufacturing network indeed increases the risks associated and the vulnerability of their supply chain. *XYZ*'s supply chain recently faced a critical shortage for a particular component due to problems with indirect suppliers. Subsequently, *XYZ* planned to assess their level of resilience for better managing their impending vulnerabilities.

In this research, a *step by step* procedure has been implemented to measure the resilience and to understand the actual resilience position in linguistic measures for *XYZ*. The procedure in brief, involves the calculation of *RFI* that indicates the level in resilience where the supply chain of *XYZ* stands and *PFI* that reflects the influence of a factor on supply chain resilience. The case study allows us to understand the implications and limitations of this research from a practical setting. The *step by step* procedure is elaborated as follows:

Step1: A committee of *five* supply chain analysts was formed for rating the attributes listed in Table 2 to assess resilience of the case supply chain. The analysts selected were experts in the field with more than *ten* years of working experience in the area of supply chains.

Step2: The committee rated the attributes on linguistic scale varying from *Worst* to *Excellent* and the weights of attributes were also determined on a scale varying from *Very Low* to *Very High*. The rating scale varies as *Worst [W], Very Poor [VP], Poor [P], Fair [F], Good [G], Very Good [VG]* and *Excellent [E]*. The weighting scale varies as *Very Low [VL], Low [L], Fairly Low [FL], Medium [M], Fairly High [FH], High [H]* and *Very High [VH]*, as detailed in Table 3.

Table 3: Linguistic assessment and the associated triangular fuzzy numbers

Rating of attributes	
Linguistic assessment	**Associated fuzzy numbers**
Worst	(0, 0.05, 0.15)
Very Poor	(0.1, 0.2, 0.3)
Poor	(0.2, 0.35, 0.5)
Fair	(0.3, 0.5, 0.7)
Good	(0.5, 0.65, 0.8)
Very Good	(0.7, 0.8, 0.9)
Excellent	(0.85, 0.95, 1.0)
Weights of attributes	
Linguistic assessment	**Associated fuzzy numbers**
Very Low	(0, 0.05, 0.15)
Low	(0.1, 0.2, 0.3)
Fairly Low	(0.2, 0.35, 0.5)
Medium	(0.3, 0.5, 0.7)
Fairly High	(0.5, 0.65, 0.8)
High	(0.7, 0.8, 0.9)
Very High	(0.85, 0.95, 1.0)

Step3: The fuzzy ratings and the fuzzy weights obtained were aggregated to mean values by applying equation (1) and (2) that are shown in Tables 4 and 5, respectively. Resilience performance is evaluated for the all attributes listed in Table 2. The value of RI is obtained considering the attributes by applying equation (3). The rating and weightings given by assessors are as follows, where X_j denotes the analyst's rating and Y_j denotes the analyst's assessment of weightings based on their importance in imparting resilience in the supply chain.

Table 4: Rating of attributes by supply chain analysts

Attributes	Performance Rating (X_{it})					Average Fuzzy Performance Rating (X_j)
	X_{j1}	X_{j2}	X_{j3}	X_{j4}	X_{j5}	
$SCRA_{A1}$*	E	E	E	VG	E	(0.82, 0.92, 0.98)
$SCRA_{A2}$	VG	E	E	E	E	(0.82, 0.92, 0.98)
$SCRA_{A3}$	E	E	E	E	E	(0.85, 0.95, 1)
$SCRA_{A4}$	E	E	E	VG	VG	(0.79, 0.89, 0.96)
$SCRA_{A5}$	E	E	E	VG	E	(0.82, 0.92, 0.98)
$SCRA_{A6}$	VG	VG	E	VG	E	(0.76, 0.86, 0.94)
$SCRA_{B1}$	VG	VG	VG	G	VG	(0.66, 0.77, 0.88)
$SCRA_{B2}$	E	VG	VG	VG	VG	(0.73, 0.83, 0.92)
$SCRA_{B3}$	G	G	VG	E	VG	(0.65, 0.77, 0.88)
$SCRA_{B4}$	VG	E	VG	E	E	(0.79, 0.89, 0.96)
$SCRA_{C1}$	VG	VG	E	VG	E	(0.76, 0.86, 0.94)
$SCRA_{C2}$	G	G	VG	G	VG	(0.58, 0.71, 0.84)
$SCRA_{C3}$	F	F	E	F	G	(0.45, 0.62, 0.78)
$SCRA_{C4}$	E	F	VG	E	E	(0.82, 0.92, 0.98)
$SCRA_{C5}$	VG	VG	VG	VG	VG	(0.7, 0.8, 0.9)
$SCRA_{D1}$	E	E	E	G	E	(0.78, 0.89, 0.96)
$SCRA_{D2}$	G	G	VG	VG	G	(0.58, 0.71, 0.84)
$SCRA_{D3}$	F	F	F	E	F	(0.41, 0.59, 0.76)
$SCRA_{D4}$	VG	VG	VG	G	VG	(0.66, 0.77, 0.88)
$SCRA_{E1}$	G	G	F	VG	VG	(0.54, 0.68, 0.82)
$SCRA_{E2}$	VG	VG	VG	VG	E	(0.73, 0.83, 0.92)
$SCRA_{E3}$	E	E	VG	E	E	(0.82, 0.92, 0.98)
$SCRA_{E4}$	VG	VG	E	VG	VG	(0.73, 0.83, 0.92)

* $SCRA_{A1}$, where 'A' indicates the main attribute 'Understanding of associated supply chain risks' and '1' indicate the sub-attribute 'Supply risk assessment' as in Table. 1. Similarly other elements of table can be read.

Table 5 Weights for attributes assigned by supply chain analysts

Attributes	Weight of Factors (Y_{it})					Average Fuzzy Weight (Y_j)
	Y_{j1}	Y_{j2}	Y_{j3}	Y_{j4}	Y_{j5}	
$SCRA_{A1}$	VH	VH	VH	H	VH	(0.82, 0.92, 0.98)
$SCRA_{A2}$	VH	VH	VH	VH	VH	(0.85, 0.95, 1)
$SCRA_{A3}$	VH	VH	VH	VH	VH	(0.85, 0.95, 1)
$SCRA_{A4}$	VH	VH	VH	H	H	(0.79, 0.89, 0.96)
$SCRA_{A5}$	VH	VH	VH	H	VH	(0.82, 0.92, 0.98)

Attributes	Weight of Factors (Y_{it})					Average Fuzzy Weight (Y_j)
	Y_{j1}	Y_{j2}	Y_{j3}	Y_{j4}	Y_{j5}	
$SCRA_{A6}$	H	H	H	H	VH	(0.73, 0.83, 0.92)
$SCRA_{B1}$	H	H	H	FH	H	(0.66, 0.77, 0.88)
$SCRA_{B2}$	H	H	FH	H	H	(0.66, 0.77, 0.88)
$SCRA_{B3}$	FH	FH	H	VH	H	(0.65, 0.77, 0.88)
$SCRA_{B4}$	VH	VH	H	VH	VH	(0.82, 0.92, 0.98)
$SCRA_{C1}$	H	H	VH	H	VH	(0.76, 0.86, 0.94)
$SCRA_{C2}$	FH	FH	H	FH	H	(0.58, 0.71, 0.84)
$SCRA_{C3}$	M	M	VH	M	FH	(0.45, 0.62, 0.78)
$SCRA_{C4}$	VH	VH	H	VH	VH	(0.82, 0.92, 0.98)
$SCRA_{C5}$	H	H	H	H	H	(0.7, 0.8, 0.9)
$SCRA_{D1}$	VH	VH	VH	FH	VH	(0.78, 0.89, 0.96)
$SCRA_{D2}$	FH	FH	H	H	FH	(0.58, 0.71, 0.84)
$SCRA_{D3}$	M	M	FH	VH	M	(0.45, 0.62, 0.78)
$SCRA_{D4}$	H	H	VH	FH	H	(0.69, 0.8, 0.9)
$SCRA_{E1}$	FH	FH	VH	H	VH	(0.61, 0.74, 0.86)
$SCRA_{E2}$	H	H	VH	H	H	(0.73, 0.83, 0.92)
$SCRA_{E3}$	VH	VH	H	VH	VH	(0.82, 0.92, 0.98)
$SCRA_{E4}$	H	H	VH	H	H	(0.73, 0.83, 0.92)

The *RFI* of the supply chain is calculated as, *RFI = (0.648, 0.748, 0.835)*

Step4: The *RFI* value was matched with the linguistic level expression set for the level of resilience *(RS) = {Definitely Resilient (DR), Extremely Resilient (ER), Very Resilient (VR), Highly Resilient (HR), Resilient (R), Fairly Resilient (FR), Slightly Resilient (SR), Low Resilient (LR), Slowly Resilient (S)* and the Euclidian distance of the membership functions is calculated for *RFI* from each linguistic level using equations (4) and (5) that is shown in Table 6.

Table 6: Euclidean distance of RS_i from *RFI*

p	M_{RFI}	$M_{RS\ S}$	M_{RS_LR}	M_{RS_SR}	M_{RS_FR}	M_{RS_R}	M_{RS_HR}	M_{RS_VR}	M_{RS_ER}	M_{RS_DR}
0	0	0	0	0	0	0	0	0	0	0
0.05	0	0.5	0	0	0	0	0	0	0	0
0.1	0	1	0	0	0	0	0	0	0	0
0.15	0	0.5	0.5	0	0	0	0	0	0	0
0.2	0	0	1	0	0	0	0	0	0	0
0.25	0	0	0.5	0.5	0	0	0	0	0	0
0.3	0	0	0	1	0	0	0	0	0	0
0.35	0	0	0	0.5	0.5	0	0	0	0	0
0.4	0	0	0	0	1	0	0	0	0	0
0.45	0	0	0	0	0.5	0.5	0	0	0	0
0.5	0	0	0	0	0	1	0	0	0	0
0.55	0	0	0	0	0	0.5	0.5	0	0	0
0.6	0	0	0	0	0	0	1	0	0	0
0.65	0	0	0	0	0	0	0.5	0.5	0	0
0.7	0	0	0	0	0	0	0	1	0	0
0.75	0.226	0	0	0	0	0	0	0.5	0.5	0

p	M_{RFI}	$M_{RS\ S}$	$M_{RS\ LR}$	$M_{RS\ SR}$	$M_{RS\ FR}$	$M_{RS\ R}$	$M_{RS\ HR}$	$M_{RS\ VR}$	$M_{RS\ ER}$	$M_{RS\ DR}$
0.8	0.698	0	0	0	0	0	0	0	1	0
0.85	0.791	0	0	0	0	0	0	0	0.5	0.5
0.9	0.209	0	0	0	0	0	0	0	0	1
0.95	0	0	0	0	0	0	0	0	0	0.5
1	0	0	0	0	0	0	0	0	0	0
Euclidian distance		**1.6455**	**1.6455**	**1.6455**	**1.6455**	**1.6455**	**1.6455**	**1.5753**	**0.5428**	**1.2242**

The values M_{RFI}, $M_{RS\ S}$, …, $M_{RS\ DR}$ represents the membership functions of the values of *RFI* and the natural language resilient expression level of resilience *RS* varying from *S* to *DR*. The Euclidian distance calculated is found to be the least with *ER*. So the supply chain taken in this case for electronics manufacturing company *XYZ* is found to be matching with the '*Extremely Resilient*' status. The matching of triangular fuzzy resilient index with the assigned linguistic labels is shown in Figure 5.

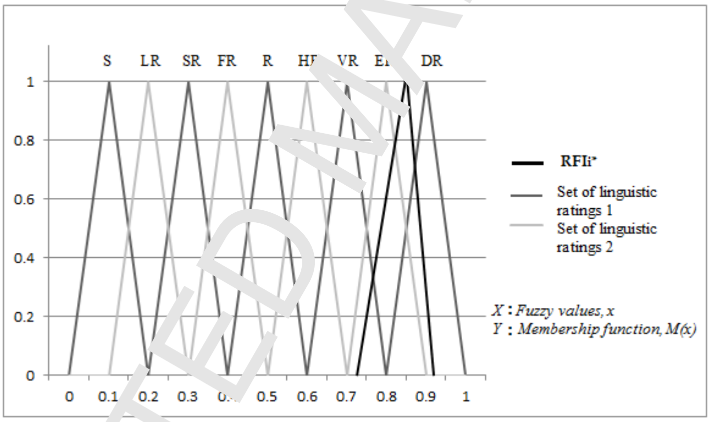

Figure 5: Matching RFI with linguistic ratings

Step 5: For calculating the Performance Fuzzy Index (*PFI*), equation (6) is employed. For obtaining a total membership function for *PFI*, equations (7) to (11) are used and the ranking score is calculated for the factors. The supply chain analyst committee identified factors with the lowest *PFI* values as critical contributing towards resilience. i.e. $SCRA_{A2}$, $SCRA_{A3}$ and $SCRA_{B4}$ (*Process risk level estimation*, *Demand risk assessment* and *Supply chain intelligence*, respectively). The ranking score is shown in Table 7. These factors need urgent attention for improving the supply chain resilience.

Table 7: Ranking of attributes

Attributes	Average Fuzzy Weight (Y_j)	Average Fuzzy Performance Rating (X_j)	$(1-Y_j)(*)X_j$	Left score ($M_L(PFI)$)	Right score ($M_R(PFI)$)	Total score ($M_T(PFI)$)
$SCRA_{A1}$	(0.82, 0.92, 0.98)	(0.82, 0.92, 0.98)	(0.148, 0.074, 0.02)	0.0211	0.9201	0.0505
$SCRA_{A2}$	(0.85, 0.95, 1)	(0.82, 0.92, 0.98)	(0.123, 0.046, 0)	0	0.9502	0.0249
$SCRA_{A3}$	(0.85, 0.95, 1)	(0.85, 0.95, 1)	(0.128,0.048, 0)	0	0.9478	0.0261
$SCRA_{A4}$	(0.79, 0.89, 0.96)	(0.79, 0.89, 0.96)	(0.166, 0.098, 0.038)	0.0404	0.8948	0.0728
$SCRA_{A5}$	(0.82, 0.92, 0.98)	(0.82, 0.92, 0.98)	(0.148, 0.074, 0.02)	0.0211	0.9201	0.0505
$SCRA_{A6}$	(0.73, 0.83, 0.92)	(0.76, 0.86, 0.94)	(0.205, 0.146, 0.075)	0.0807	0.8448	0.1179
$SCRA_{B1}$	(0.66, 0.77, 0.88)	(0.66, 0.77, 0.88)	(0.224, 0.177, 0.106)	0.1141	0.8143	0.1499
$SCRA_{B2}$	(0.66, 0.77, 0.88)	(0.73, 0.83, 0.92)	(0.248, 0.191, 0.11)	0.1197	0.7975	0.1611
$SCRA_{B3}$	(0.65, 0.77, 0.88)	(0.65, 0.77, 0.88)	(0.223, 0.177, 0.106)	0.1141	0.8135	0.1503
$SCRA_{B4}$	(0.82, 0.92, 0.98)	(0.79, 0.89, 0.96)	(0.142, 0.071, 0.019)	0.0200	0.9236	0.0482
$SCRA_{C1}$	(0.76, 0.86, 0.94)	(0.76, 0.86, 0.94)	(0.182, 0.12, 0.056)	0.0598	0.8721	0.0939
$SCRA_{C2}$	(0.58, 0.71, 0.84)	(0.58, 0.71, 0.84)	(0.244, 0.206, 0.134)	0.1444	0.7859	0.1793
$SCRA_{C3}$	(0.45, 0.62, 0.78)	(0.45, 0.62, 0.78)	(0.248, 0.236, 0.172)	0.1838	0.7611	0.2113
$SCRA_{C4}$	(0.82, 0.92, 0.98)	(0.82, 0.92, 0.98)	(0.148, 0.074, 0.02)	0.0211	0.9201	0.0505
$SCRA_{C5}$	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.21, 0.16, 0.09)	0.0968	0.8316	0.1326
$SCRA_{D1}$	(0.78, 0.89, 0.96)	(0.78, 0.89, 0.96)	(0.172, 0.098, 0.038)	0.0404	0.8942	0.0731
$SCRA_{D2}$	(0.58, 0.71, 0.84)	(0.58, 0.71, 0.84)	(0.244, 0.206, 0.134)	0.1444	0.7859	0.1793
$SCRA_{D3}$	(0.45, 0.62, 0.78)	(0.41, 0.59, 0.76)	(0.226, 0.224, 0.167)	0.1771	0.7756	0.2008
$SCRA_{D4}$	(0.69, 0.8, 0.9)	(0.66, 0.77, 0.88)	(0.205, 0.154, 0.088)	0.0942	0.8377	0.1282
$SCRA_{E1}$	(0.61, 0.74, 0.86)	(0.54, 0.68, 0.82)	(0.211, 0.177, 0.115)	0.1226	0.8168	0.1529
$SCRA_{E2}$	(0.73, 0.83, 0.92)	(0.73, 0.83, 0.92)	(0.197, 0.141, 0.074)	0.0793	0.8506	0.1143
$SCRA_{E3}$	(0.82, 0.92, 0.98)	(0.82, 0.92, 0.98)	(0.148, 0.074, 0.02)	0.0211	0.9201	0.0505
$SCRA_{E4}$	(0.73, 0.83, 0.92)	(0.73, 0.83, 0.92)	(0.197, 0.141, 0.074)	0.0793	0.8506	0.1143

4. Results and Discussion

We have taken *five* supply chain strategies and *twenty three* attributes of resilience in this research with typical focus on electronics manufacturing firms. A *seven* point scale of rating was judiciously assigned to rate the quantitative and qualitative attributes of resilience. By calculating *RFI*, it is possible to identify the level of resilience of a supply chain and thus the level of vulnerability of supply chain could also be determined. *PFI* helps in finding the level of contribution of an attribute towards the supply chain resilience. From the values of *PFI*, it is possible to identify the critical attributes contributing to the resilience of supply chain as a whole. Also it is possible to identify the attributes contributing least towards the resilience of supply chain.

The critical attributes highly contributing to the supply chain resilience needs urgent attention and the attributes are identified as $SCRA_{A2}$, $SCRA_{A3}$ & $SCRA_{B4}$ (*Process risk level estimation, Demand risk assessment and Supply chain intelligence*, respectively). However, the company *XYZ* needs to improve in some areas for improving its resilience. The *four* factors with the highest values of *PFI* need to be improved for increasing the level of resilience. These factors are identified as $SCRA_{C3}$, $SCRA_{D3}$, $SCRA_{C2}$ and $SCRA_{D2}$ (*Abolition of functional silos, Postponement verdicts, Velocity and Parallel processes*, respectively).

How far resilience of supply chain can be improved by improving the rating of factors $SCRA_{C3}$, $SCRA_{D3}$, $SCRA_{C2}$ and $SCRA_{D2}$? To answer this question, sensitivity analysis was carried out. The improved values of *RFI* (RFI_j^*) by improving the average fuzzy ratings (X_j^*) for factors *j* are shown in Table 8. The maximum performance rating the factors can achieve and the corresponding values of RFI_j^* are given in the last row of Table 8. The improvement in the level of resilience by maximum improvement in the rating of factor $SCRA_{C3}$ is shown in Figure 6.

Table 8: Sensitivity analysis

Sl No.	Improved Average Rating (Xj^*)	Improved RFI (RFI_j^*) for sub- attributes *j*			
		$SCRA_{C3}$	$SCRA_{D3}$	$SCRA_{C2}$	$SCRA_{D2}$
1	(0.60, 0.70, 0.80)	(0.730, 0.834, 0.919)	(0.731, 0.835, 0.920)	(0.727, 0.831, 0.916)	(0.727, 0.831, 0.916)
2	(0.60, 0.75, 0.80)	(0.730, 0.836, 0.919)	(0.731, 0.837, 0.920)	(0.727, 0.833, 0.916)	(0.727, 0.833, 0.916)
3	(0.60, 0.75, 0.85)	(0.730, 0.836, 0.921)	(0.731, 0.837, 0.921)	(0.727, 0.833, 0.918)	(0.727, 0.833, 0.918)
4	(0.65, 0.75, 0.85)	(0.732, 0.836, 0.921)	(0.733, 0.837, 0.921)	(0.729, 0.833, 0.918)	(0.729, 0.833, 0.918)
5	(0.65, 0.80, 0.85)	(0.732, 0.837, 0.921)	(0.733, 0.838, 0.921)	(0.729, 0.835, 0.918)	(0.729, 0.835, 0.918)
6	(0.65, 0.80, 0.90)	(0.732, 0.837, 0.922)	(0.733, 0.838, 0.923)	(0.729, 0.835, 0.920)	(0.729, 0.835, 0.920)
7	(0.70, 0.80, 0.90)	(0.733, 0.837, 0.922)	(0.734, 0.838, 0.923)	(0.730, 0.835, 0.920)	(0.730, 0.835, 0.920)
8	(0.70, 0.85, 0.90)	(0.733, 0.839, 0.922)	(0.734, 0.840, 0.923)	(0.730, 0.837, 0.920)	(0.730, 0.837, 0.920)
9	(0.70, 0.85, 0.95)	(0.733, 0.839, 0.924)	(0.734, 0.840, 0.925)	(0.730, 0.837, 0.922)	(0.730, 0.837, 0.922)
10	(0.75, 0.85, 0.95)	(0.734, 0.839, 0.924)	(0.735, 0.840, 0.925)	(0.732, 0.837, 0.922)	(0.732, 0.837, 0.922)
11	(0.75, 0.90, 0.95)	(0.734, 0.841, 0.924)	(0.735, 0.842, 0.925)	(0.734, 0.837, 0.922)	(0.734, 0.837, 0.922)
12	(0.75, 0.90, 1.00)	(0.734, 0.841, 0.926)	(0.735, 0.842, 0.927)	(0.734, 0.839, 0.922)	(0.734, 0.839, 0.922)
13	(0.80, 0.90, 1.00)	(0.736, 0.841, 0.926)	(0.737, 0.842, 0.927)	(0.734, 0.839, 0.924)	(0.734, 0.839, 0.924)
Maximum RFI^* by combination of attributes *j*		($SCRA_{C3}$)	($SCRA_{(C3+D3)}$)	($SCRA_{(C3+D3+C2)}$)	($SCRA_{(C3+D3+C2+D2)}$)
		(0.736, 0.841, 0.926)	(0.746, 0.851, 0.935)	(0.754, 0.858, 0.941)	(0.762, 0.865, 0.948)

The improvement in the level of resilience for maximum improvement in combining factors $SCRA_{C3}$ and $SCRA_{D3}$ is shown in Figure 7. The maximum improvement in resilience level by improving all the *four* factors, $SCRA_{C3}$, $SCRA_{D3}$, $SCRA_{C2}$ and $SCRA_{D2}$ to their maximum ratings is shown in Figure 8.

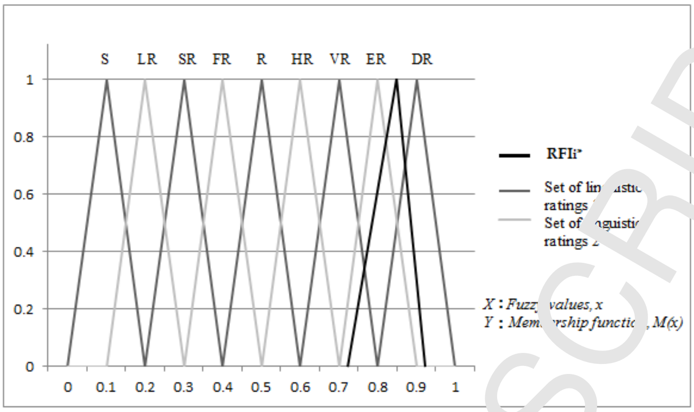

Figure 6: *RFI for the highest rating of SCRA$_{C3}$ matching with linguistic ratings**

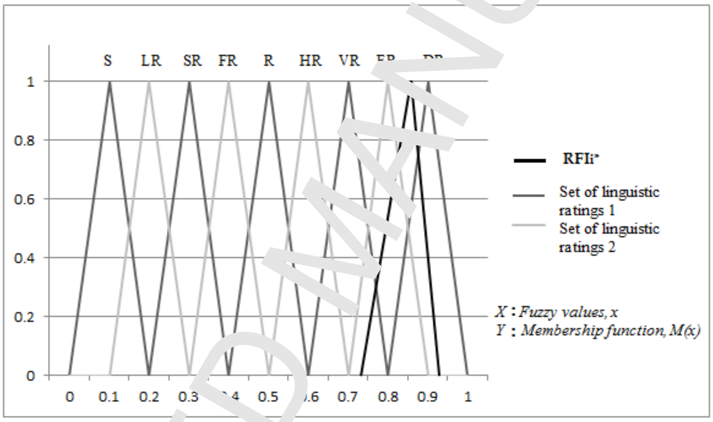

Figure 7: *RFI for the highest ratings of SCRA$_{C3}$ and SCRA$_{D3}$, matching with linguistic ratings**

The results of sensitivity analysis shows that there is a full possible shift from *'Extremely Resilient'* to *'Definitely Resilient'* level, by improving the performance rating of the attributes to their maximum possible values.

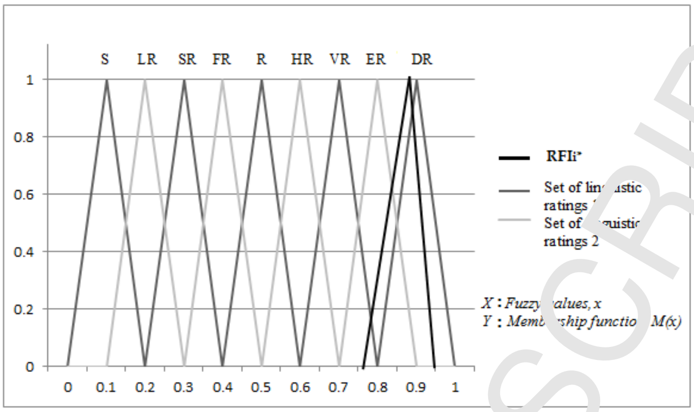

Figure 8: *RFI for the highest ratings of SCRA$_{C3}$, SCRA$_{D3}$ SCRA$_{C2}$ and SCRA$_{D2}$ matching with linguistic ratings**

On analysis of the results, it is seen that proper risk assessment is important for building resilience in supply chains. Among various risk assessments, process risk level estimation and demand risk assessments emerges as most important for the case supply chain considered for the study. When process risks are reduced, the risks of rejection of products can also be reduced and when the demand risks are reduced, the bullwhips in supply chains can be reduced. Demand risks can be reduced by employing proper forecasting techniques by combining qualitative and quantitative forecasting models to accurately predicting the expected demand and to reducing the bullwhips.

Supply chain intelligence also plays a critical role in building resilience in supply chains, where the knowledge created and shared among partners can help in reducing bullwhips. Proper knowledge sharing increases the collaboration capabilities of the supply chain and thus enabling the supply chain to bend together at times of disruptions rather than breaking at a point. Also, it helps the supply chain to achieving several other collaborative practices such as: Vendor Managed Inventory (VMI), Collaborative Planning, Forecasting and Replenishment (CPFR), etc. Thus, supply chain intelligence can lead to supply chain resilience by enabling the proper utilization of available buffers (capacity, inventory, and time) in the supply chain.

5. Conclusions and Scope of future works

Supply chain risk management and resilience are gaining prominence in recent years. Focus of this research was to ascertain, measure and improve the level of resilience of supply chains. Various attributes imparting resilience to the supply chain were identified and analyzed. The procedure for calculating a fuzzy index for resilience is developed by considering attributes seen in a typical electronics supply chain. The gaps towards resilience were measured by using a fuzzy performance measurement system. This research suggested an approach for the companies to know their status of resilience in the form of an index through identifying attributes for resilience, rating the attributes and by finding their respective weightings. The identification of the level of the resilience of a company at any particular instant is important for taking strategic level decisions. Thus, resilience check before any strategy implementation helps in identifying major areas of improvement. This can reduce vulnerability of supply chain as a whole.

There are a few limitations of this research. Since the model does not consider the changes in strategies and attributes for different time periods, *'the time to recover'* element in the resilience measurement of the supply chain was not considered for the study. This can be a direction to future research. The fuzzy values associated for a linguistic level of assessment is assumed to be triangular in an interval, which might have reflected in the final results. The weighting and rating of attributes by committee members depends upon their knowledge and familiarity with the firm, its operations, etc. Thus, the biasing of committee members towards some of the attributes might have also affected the results. The model can be further extended by making into a multi stage model, where the key specific points of resilience enhancers and the points of poor performances can be identified. The resilience and sustainability issues can be combined to make a tradeoff between factors imparting sustainability and resilience. Efforts are also recommended in the direction of constructing and maintaining a resilient- sustainable supply chain. Future research could also focus upon detailed analysis of risk profiles and thus devising the operation strategy of supply chain for enhanced resilience capabilities.

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Highlights

- Identify, ascertain, measure and improve the level of resilience of firms.
- Several strategies, practices and attributes contributing to the resilience of supply chains were studied.
- Electronics manufacturing supply chains were considered for the study.
- Fuzzy measurement system is used to access the level of resilience.
- A case evaluation was carried out in an Indian electronics manufacturing supply chain.
- Resilience status of the case supply chain is matching with '*Extremely Resilient*' level.